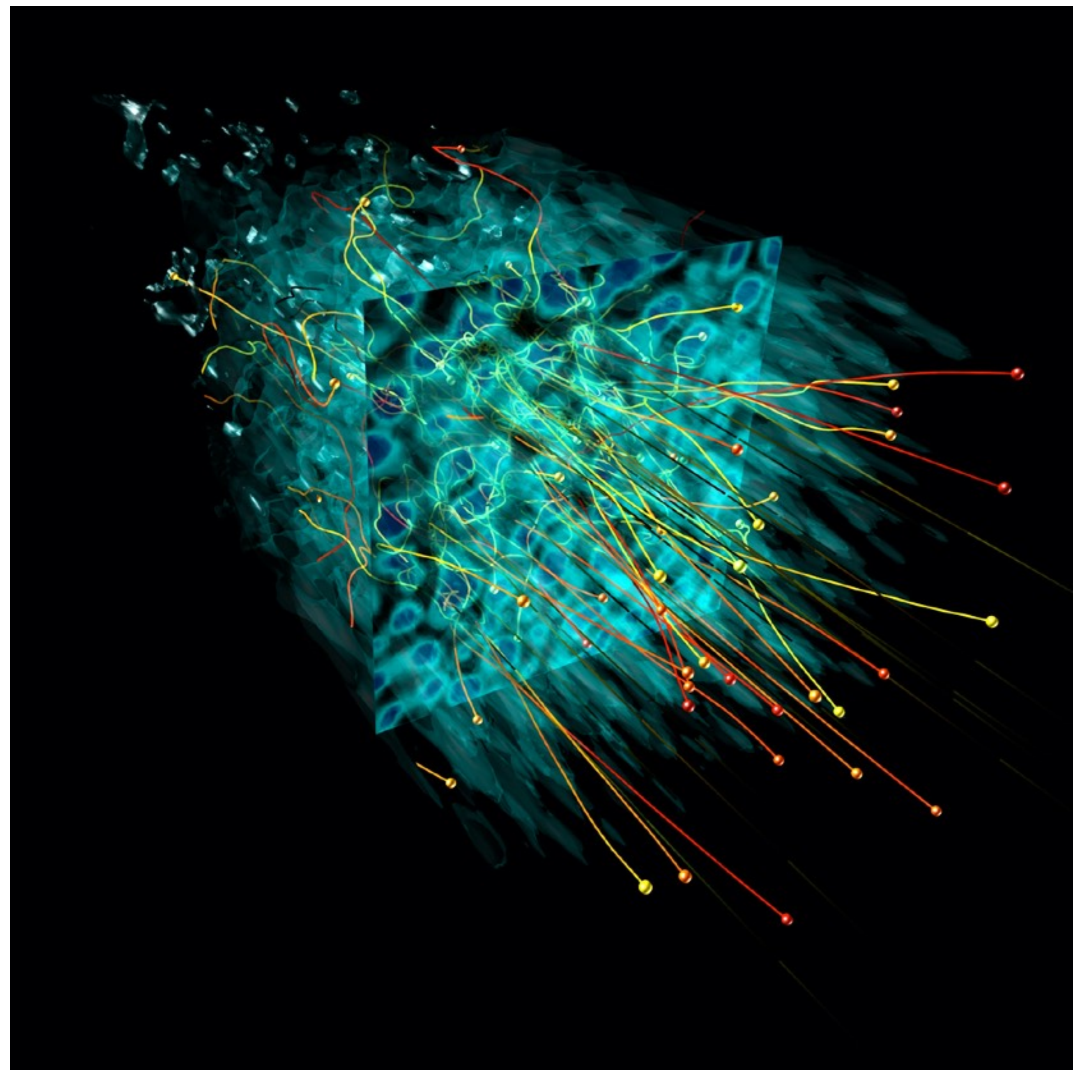
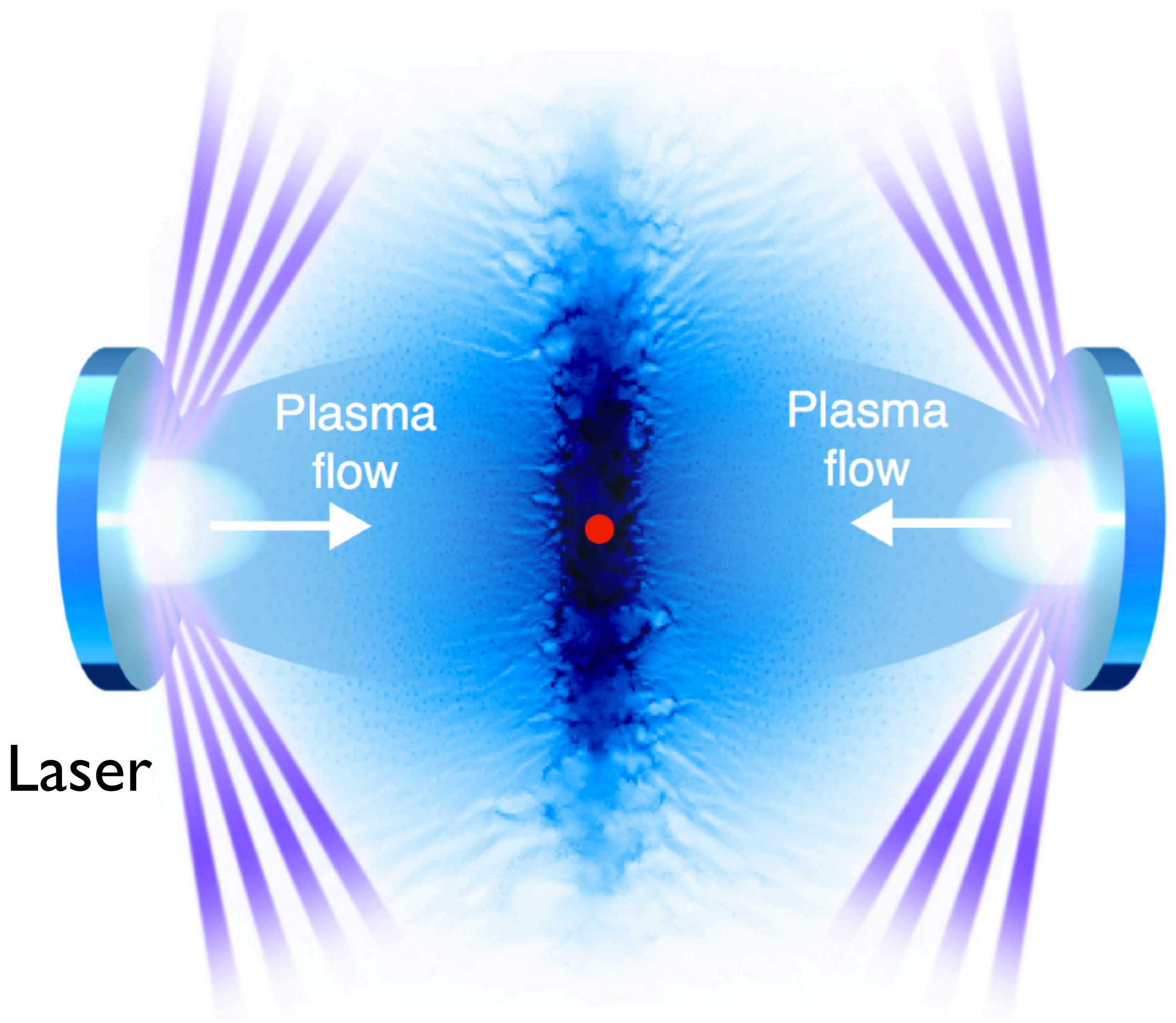
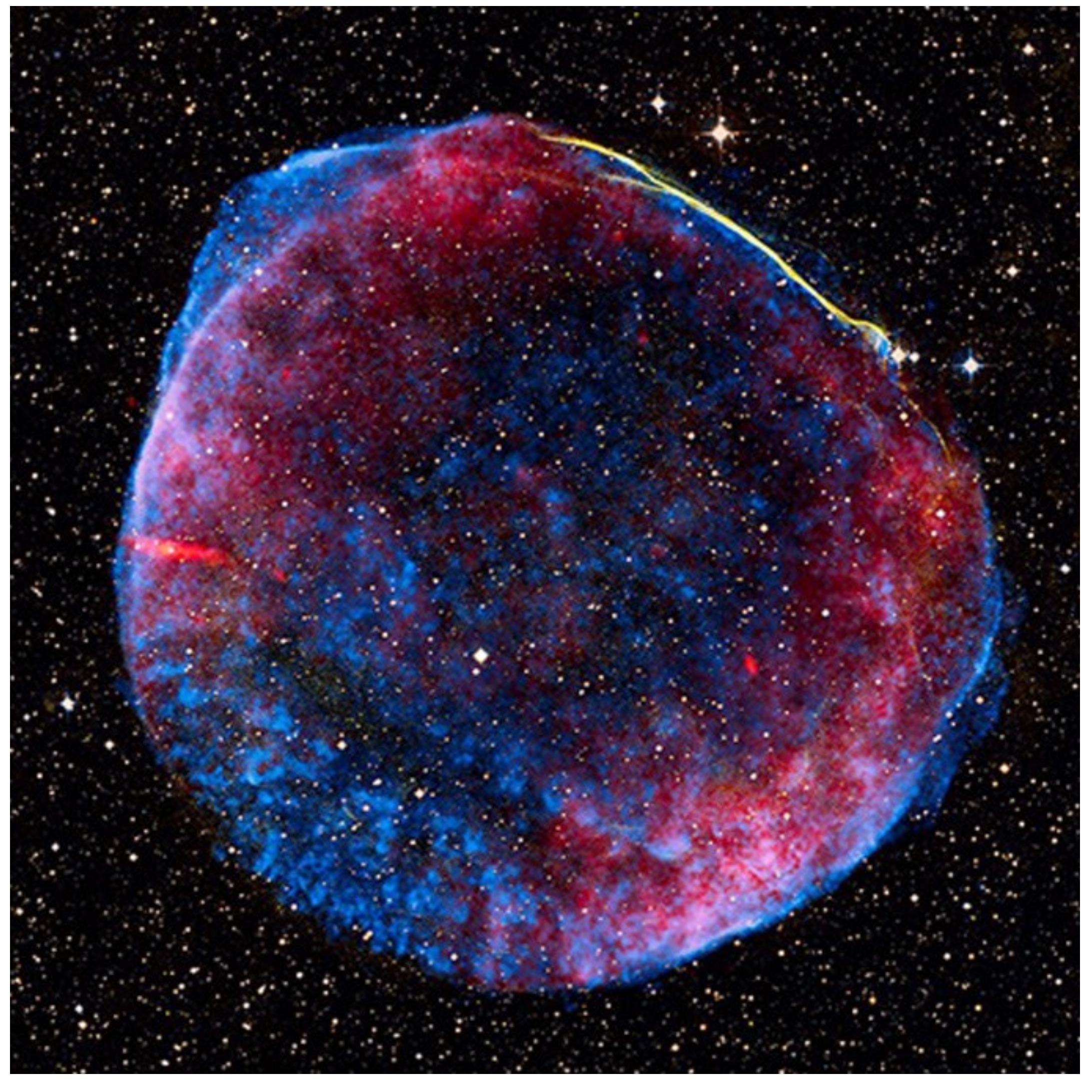
Particle acceleration in shocks: from simulations to observations via laboratory experiments

Frederico Fiuza

fiuza@slac.stanford.edu







U.S. DEPARTMENT OF ENERGY Office of Science

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Outline

Shock waves as cosmic particles accelerators

Observations and standard model of particle acceleration

Importance of plasma microphysics for shock acceleration

Numerical simulations reveal rich physics interplay

New opportunities being opened by laboratory experiments

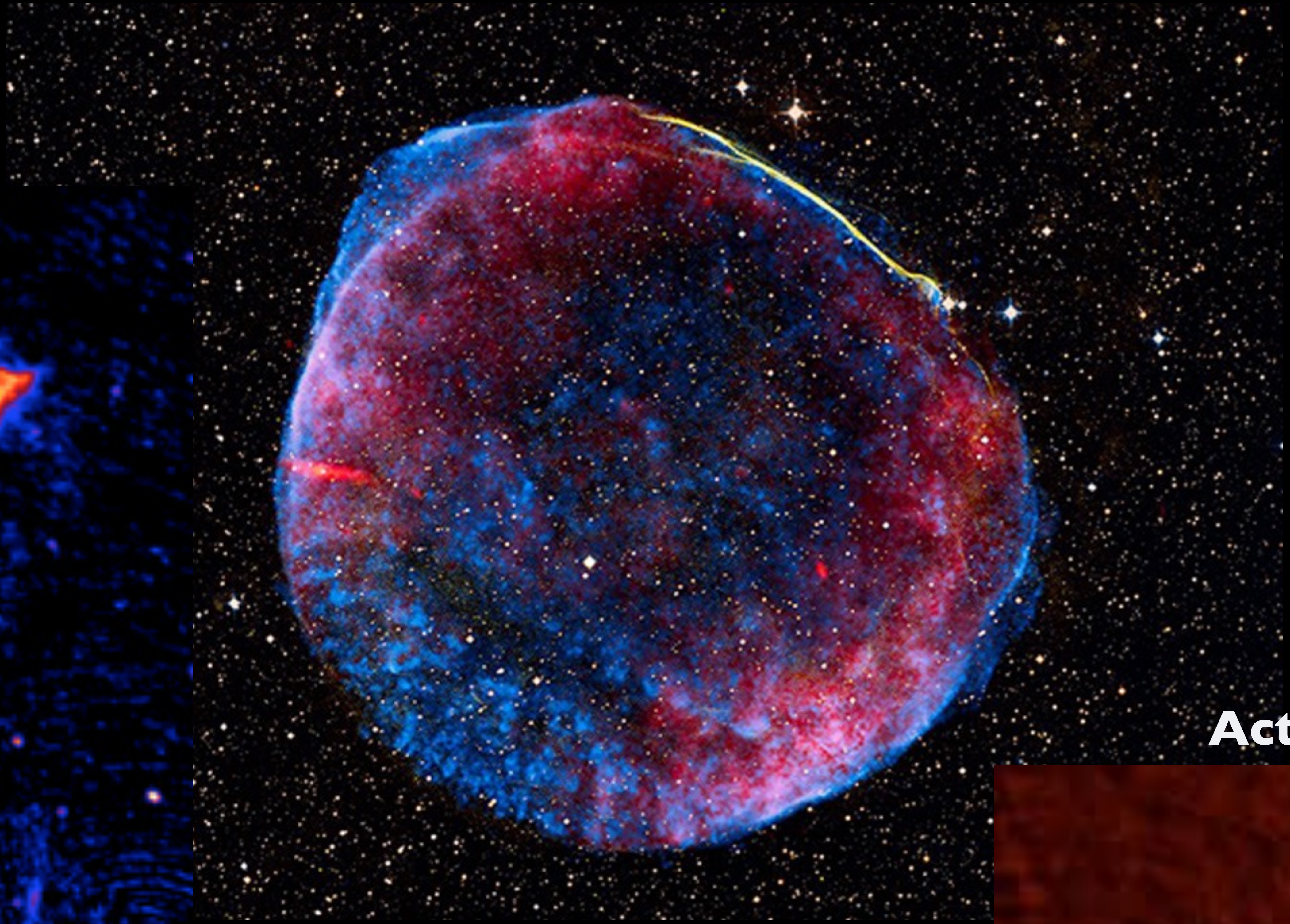
Laser-driven shock waves are enabling controlled studies of shock microphysics

Exciting perspectives ahead

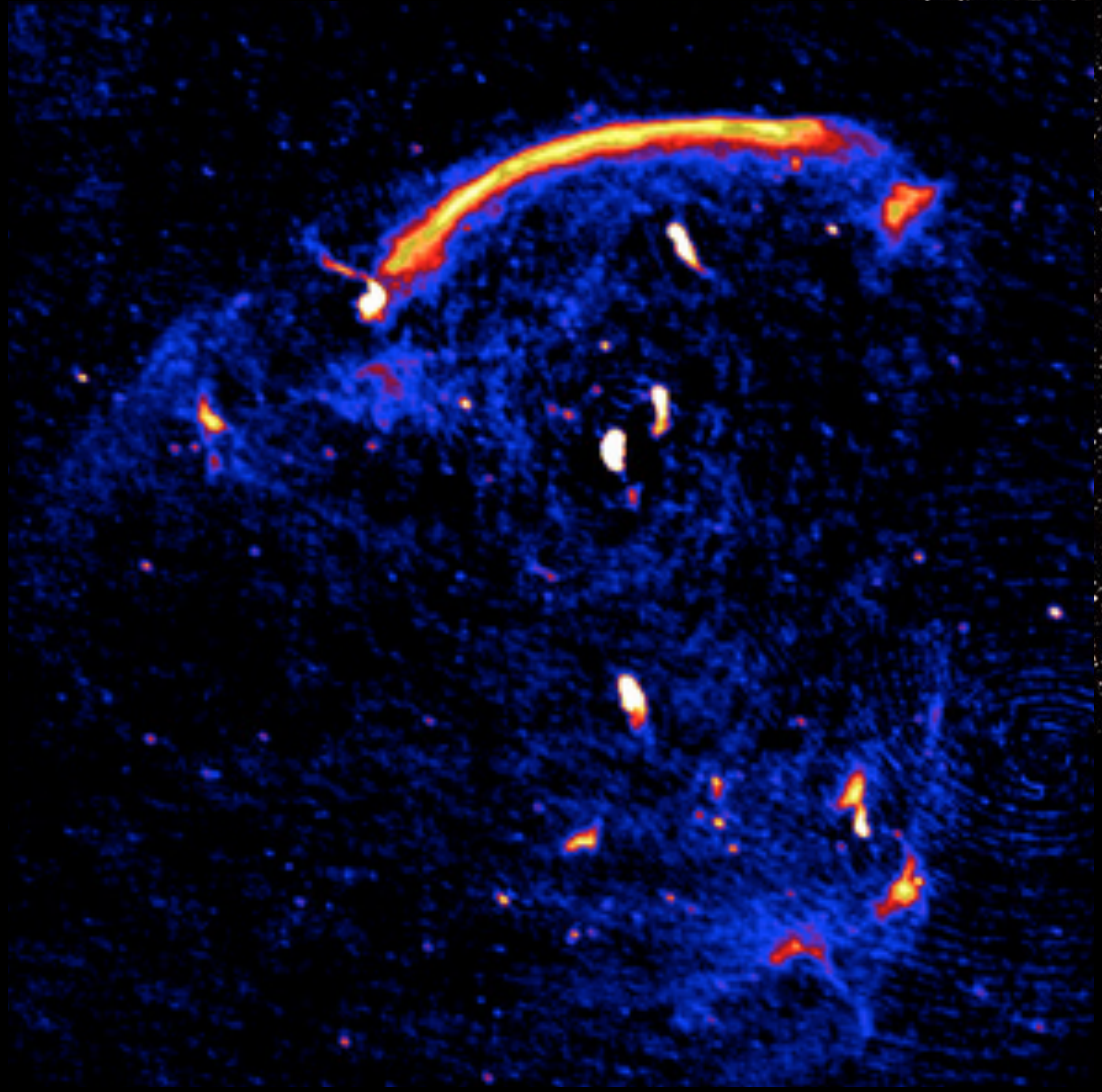
Intense lasers and particle beams can enable studies in relativistic regime

Shock waves as cosmic particle accelerators

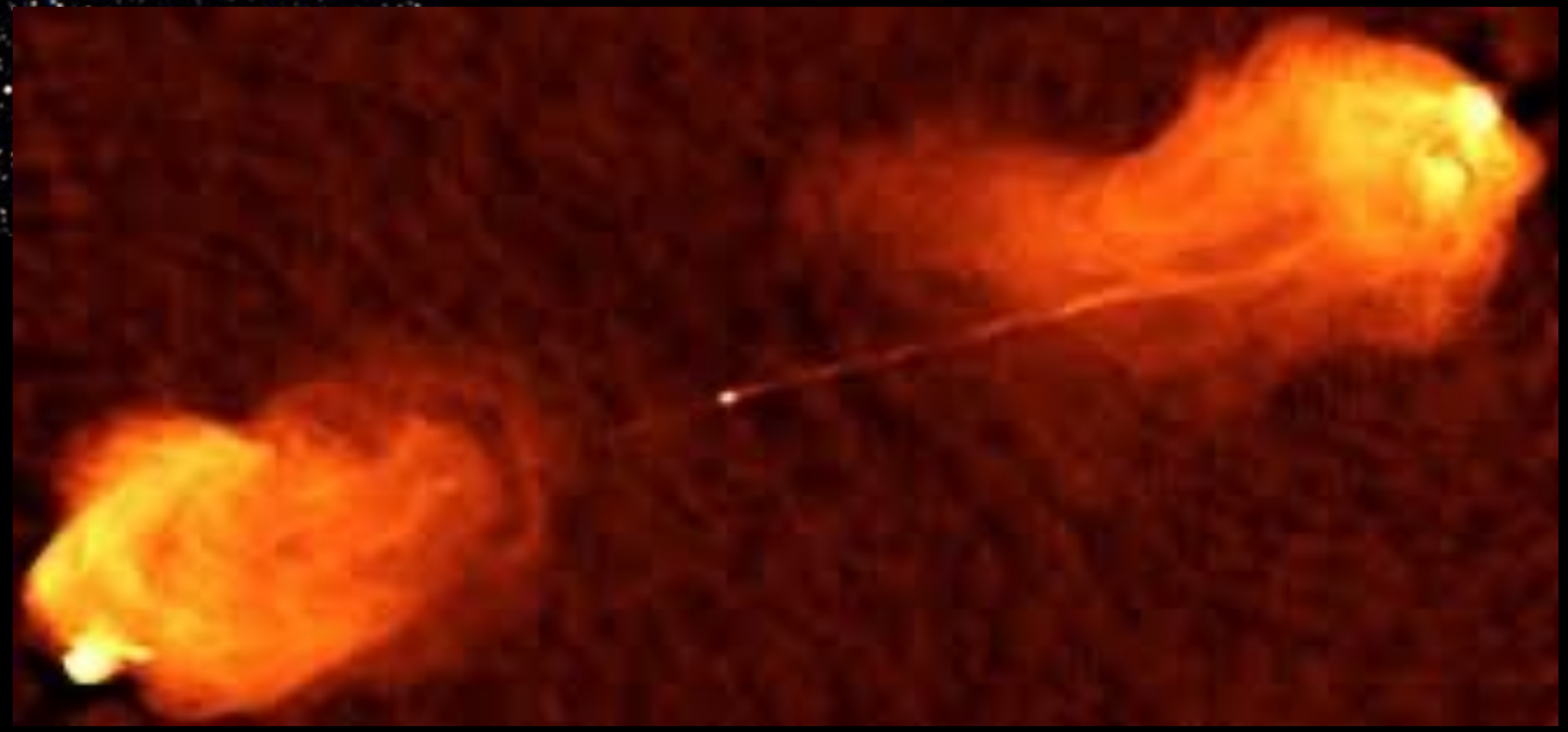
Supernova remnants



Galaxy clusters



Active Galactic Nuclei jets



Astrophysical shocks are known to be efficient particle accelerators

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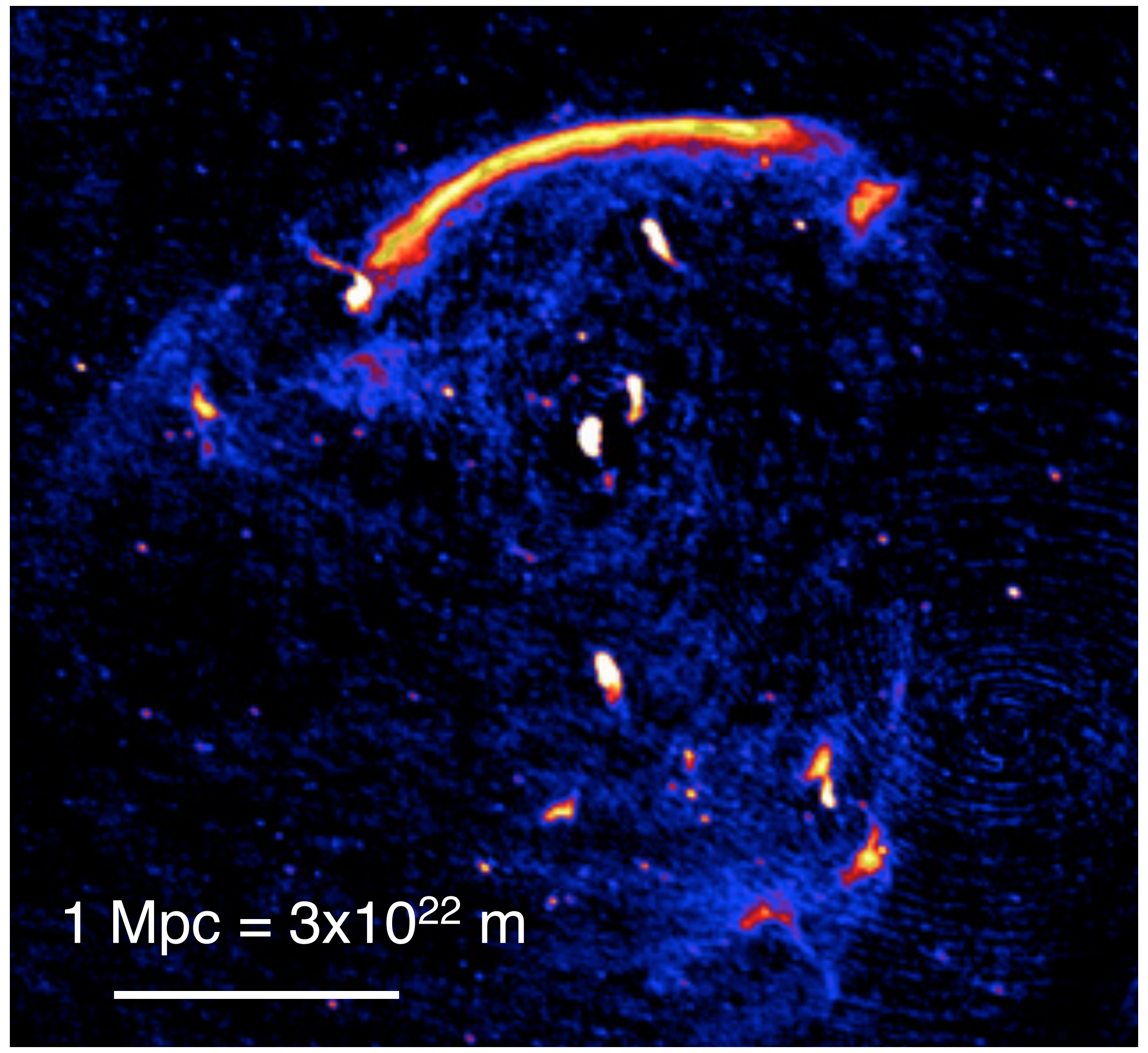
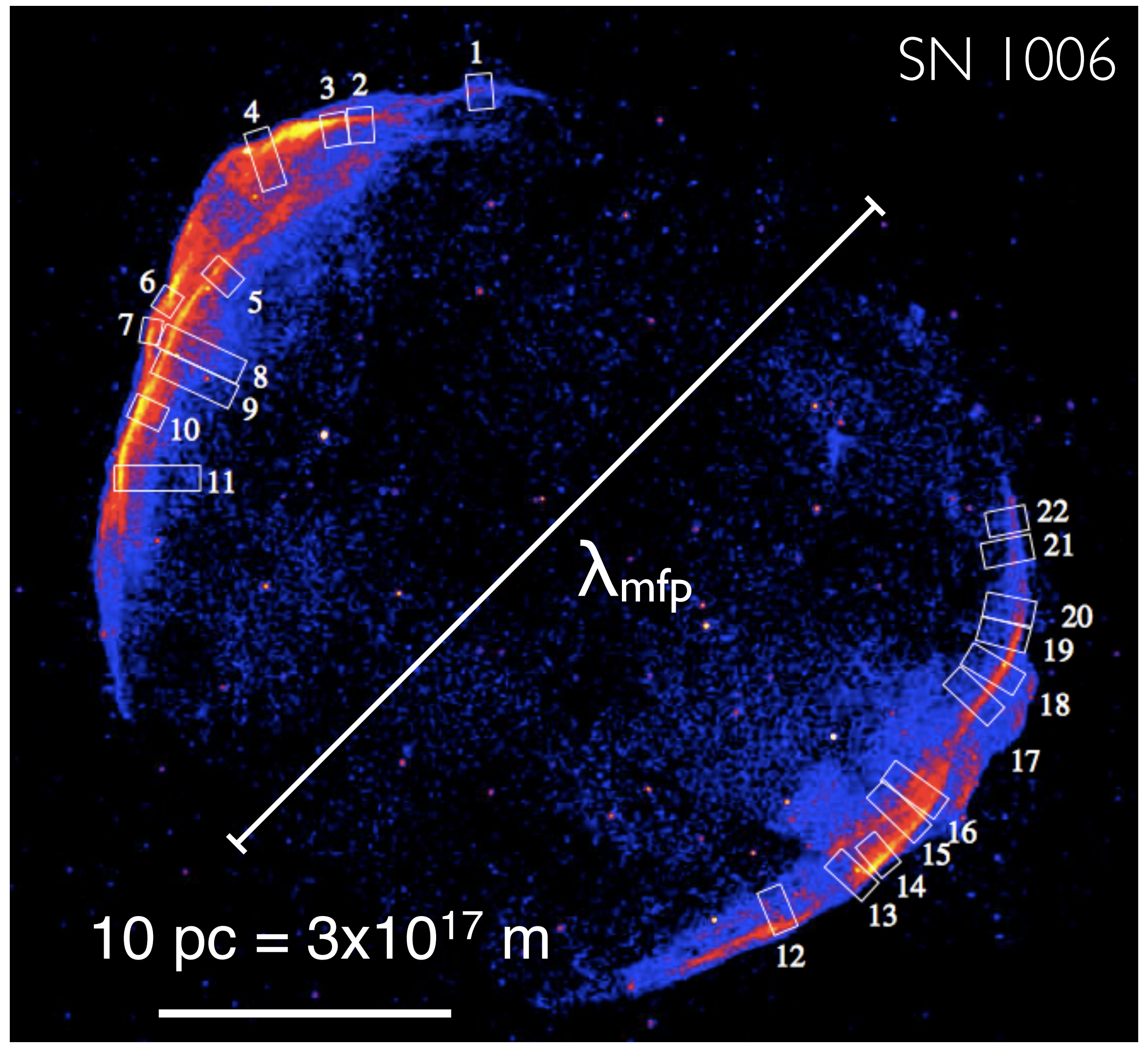
Galaxy clusters

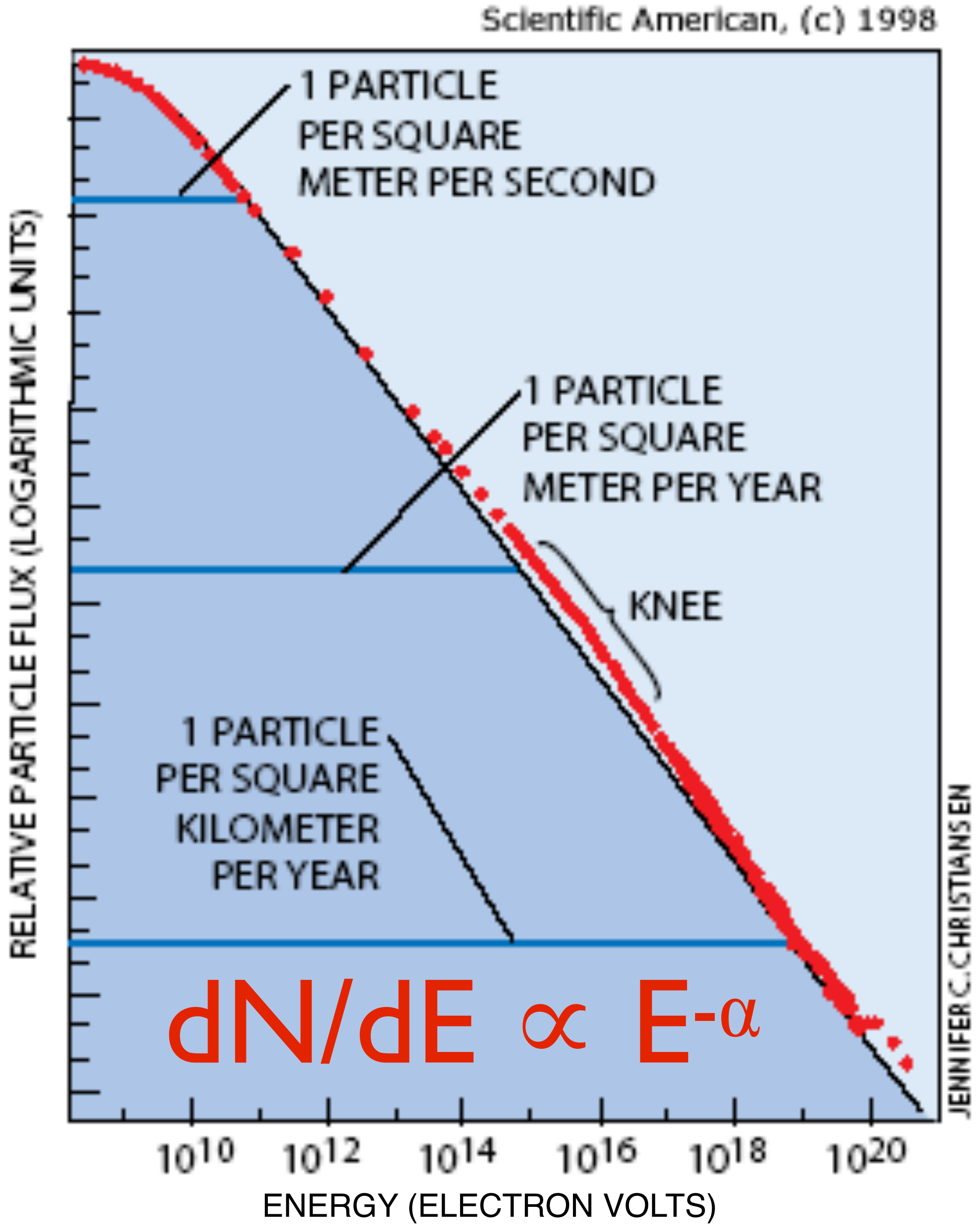


Supernovae remnants



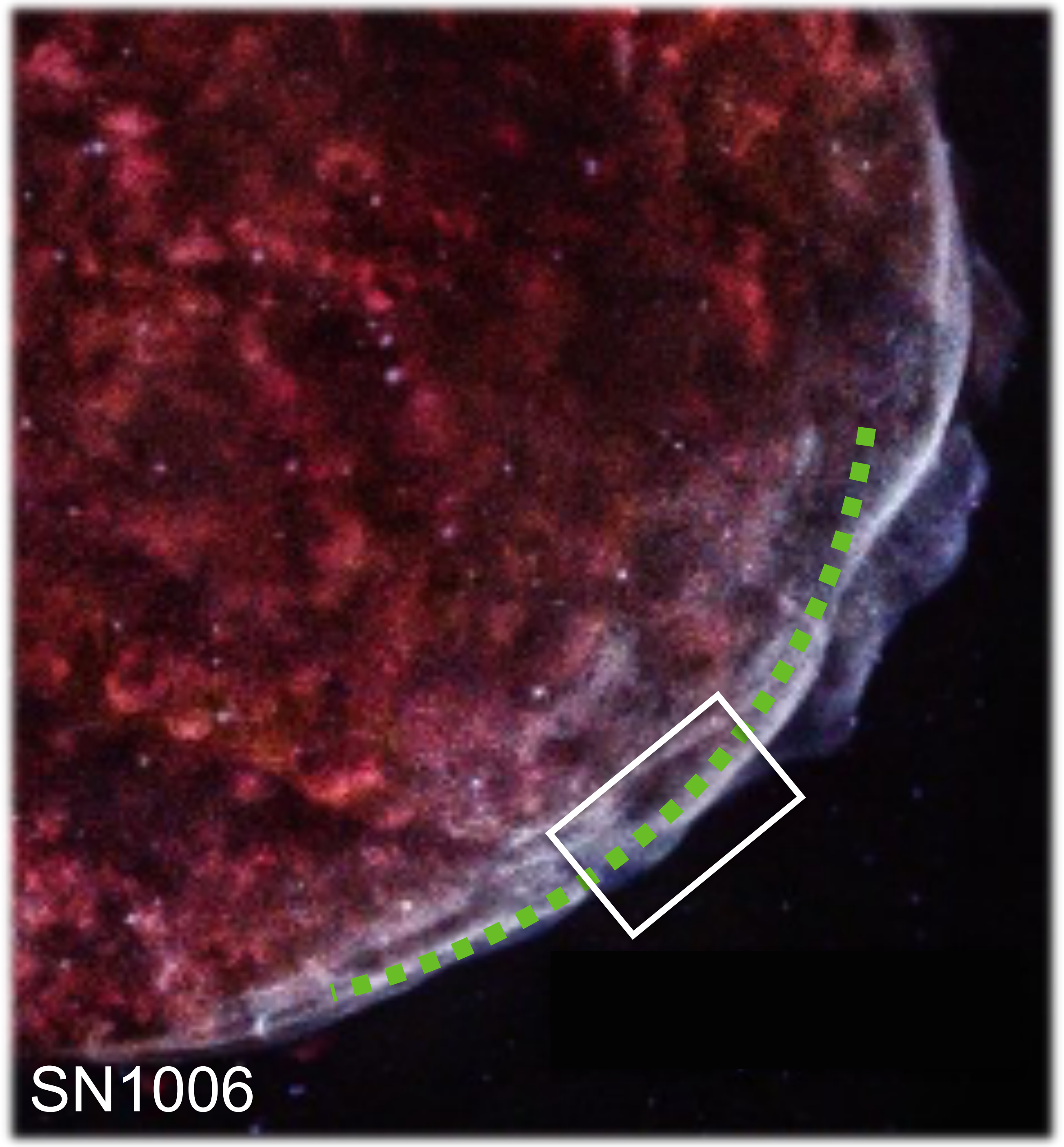
Gamma ray bursts

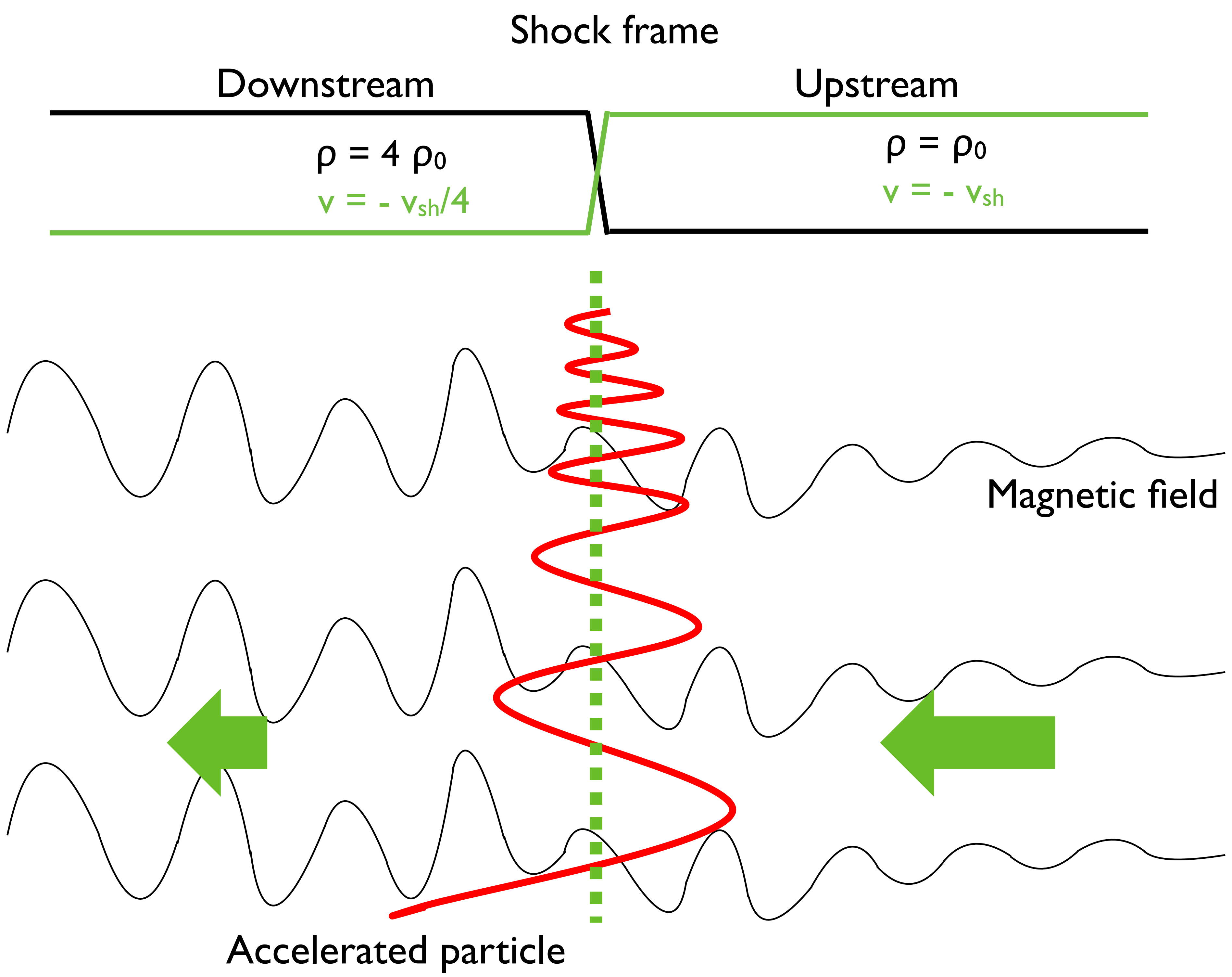
What controls CR acceleration?



- Shocks are collisionless (mediated by plasma fields rather than Coulomb collisions)
- Span a wide range of scales and conditions:
  - non-relativistic (v = 100 - 1000 km/s) to highly relativistic ($\gamma = 10^6$)
  - weakly magnetized to highly magnetized
- Emit radiation across entire EM spectrum: radio to γ-rays
- Can accelerate particles to very high energies: up to 10^{21} eV?

I st order Fermi acceleration in shocks





I st order Fermi mechanism in shocks*
(a.k.a. diffusive shock acceleration)

Fractional energy gain per shock crossing:

$$\frac{\Delta\epsilon}{\epsilon} = \frac{v_{sh}}{c}$$

Fractional particle loss per shock crossing:

$$\frac{dn}{n} = -\frac{v_{sh}}{c}$$

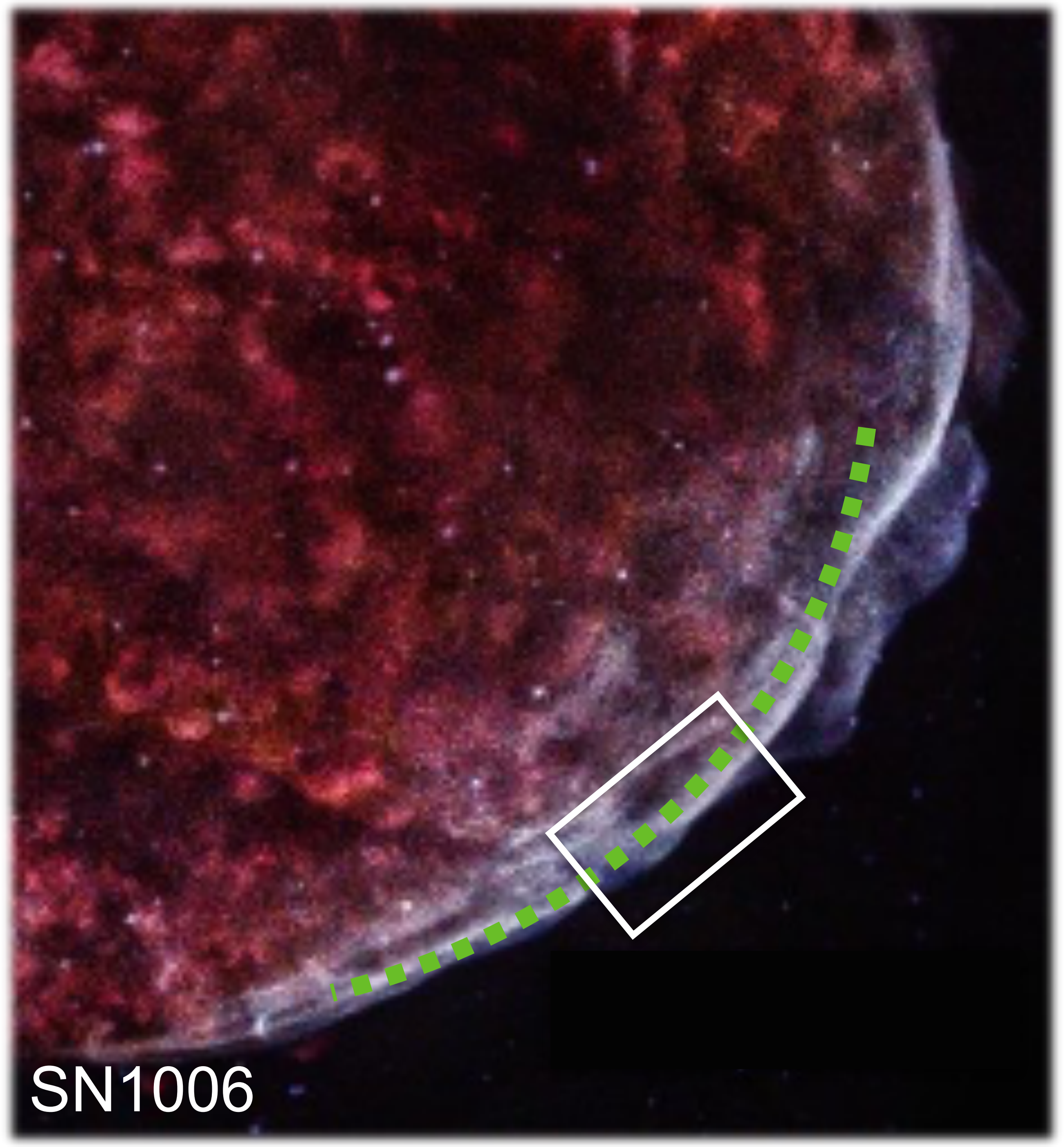
Power-law spectrum:

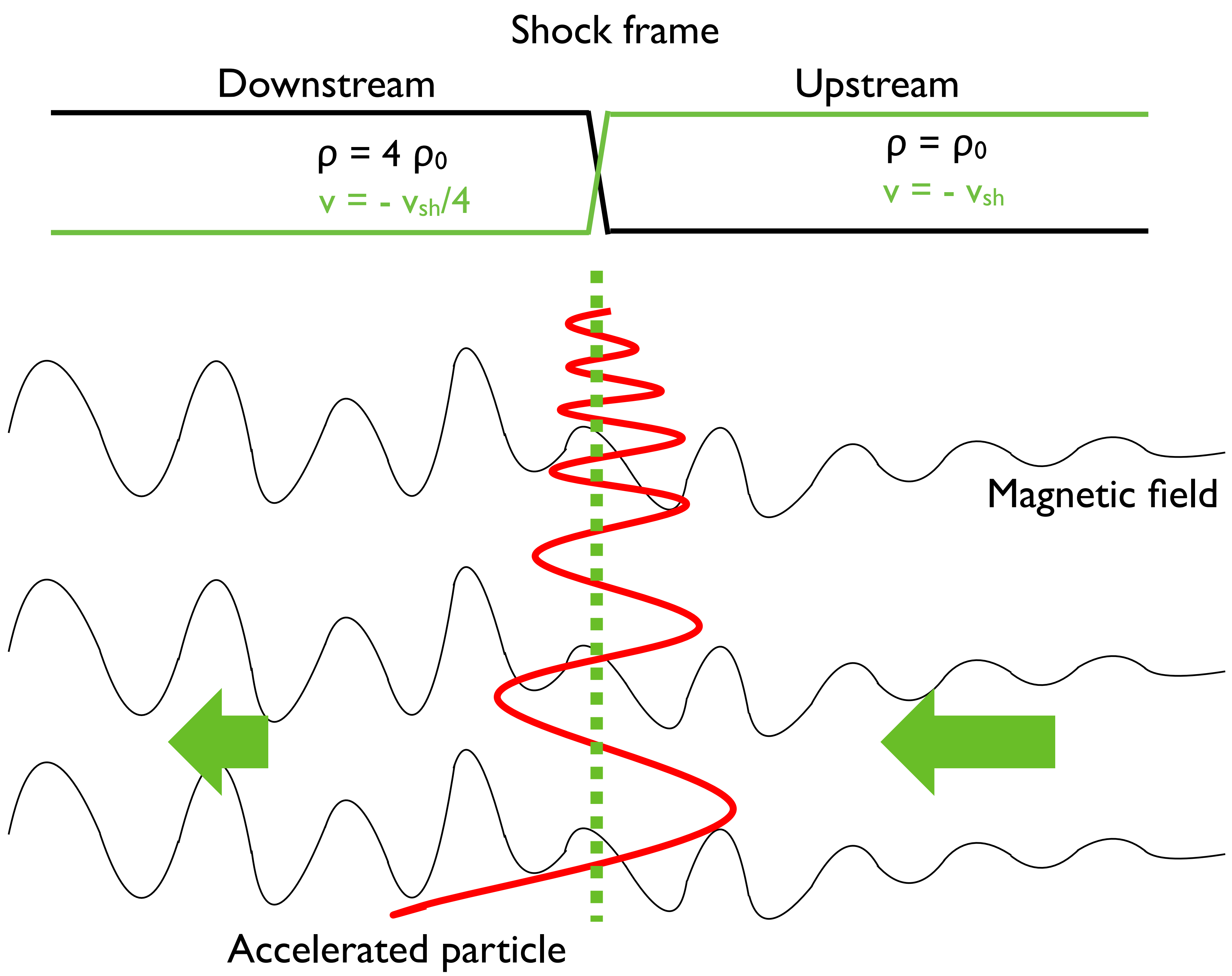
$$\frac{dN}{d\epsilon} \propto \epsilon^{-2}$$

Elegant solution to power-law particle acceleration across wide range of systems

*** Krymskii 1977, Axford, Leer, Skadron 1977, Bell 1978, Blandford & Ostriker 1978**

Requires strong turbulent (disordered) magnetic fields





Efficient particle scattering requires **strong magnetic fluctuations**

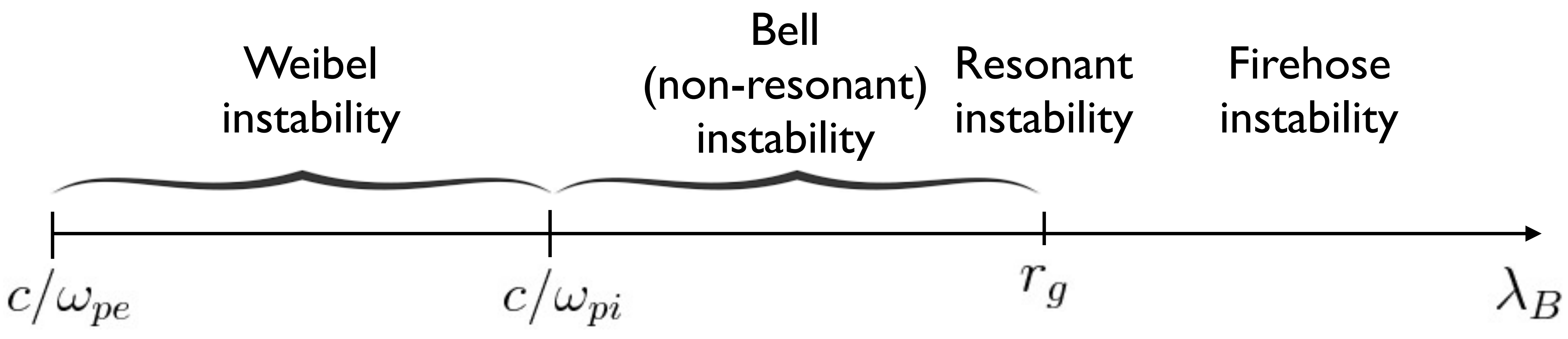
$$\delta B \gg B$$

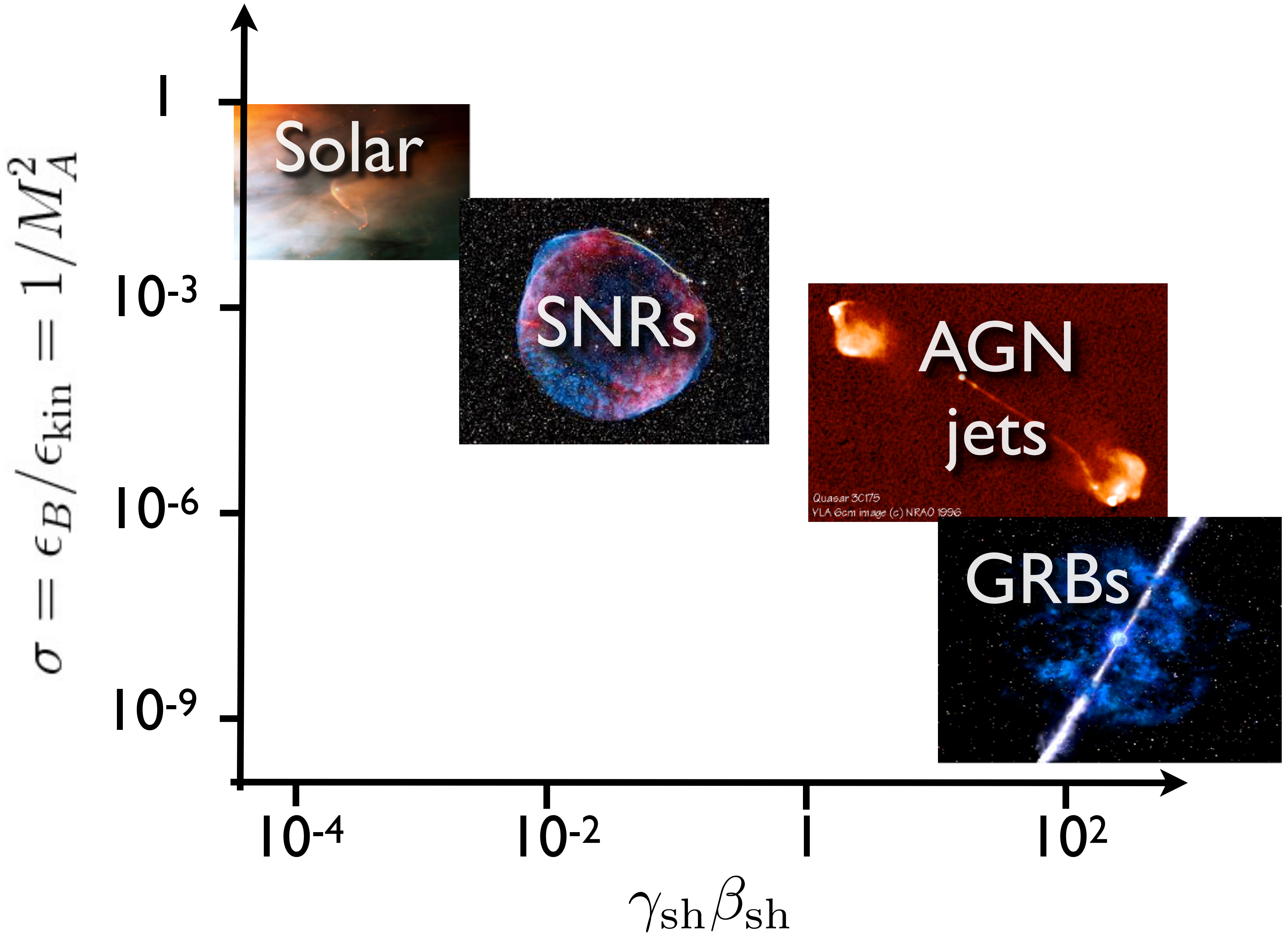
Fastest acceleration if scale of fluctuations comparable to Larmor radius of particles (Bohm diffusion)

$$\lambda_B \sim r_g$$

X-ray observations indicate **nonadiabatic magnetic field amplification** ($\delta B/B \sim 10^2$) near the shock front (Bamba et al. 2003, 2005, Vink 2012)

Which processes control magnetic field amplification?

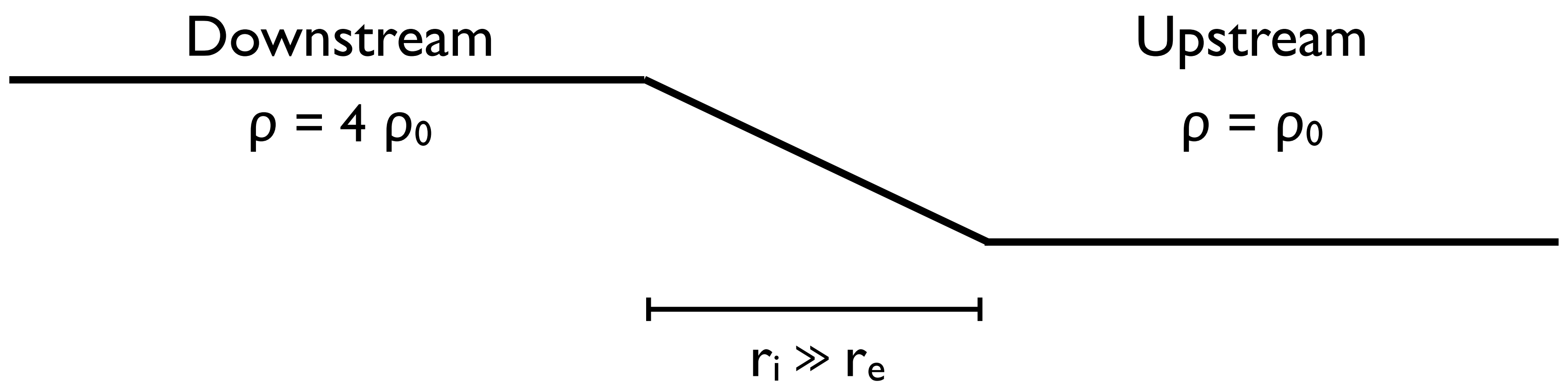




Interplay between different instabilities is critical for particle acceleration but it is not clear how it depends on the shock and ambient plasma conditions

Riding giants: the puzzle of particle injection

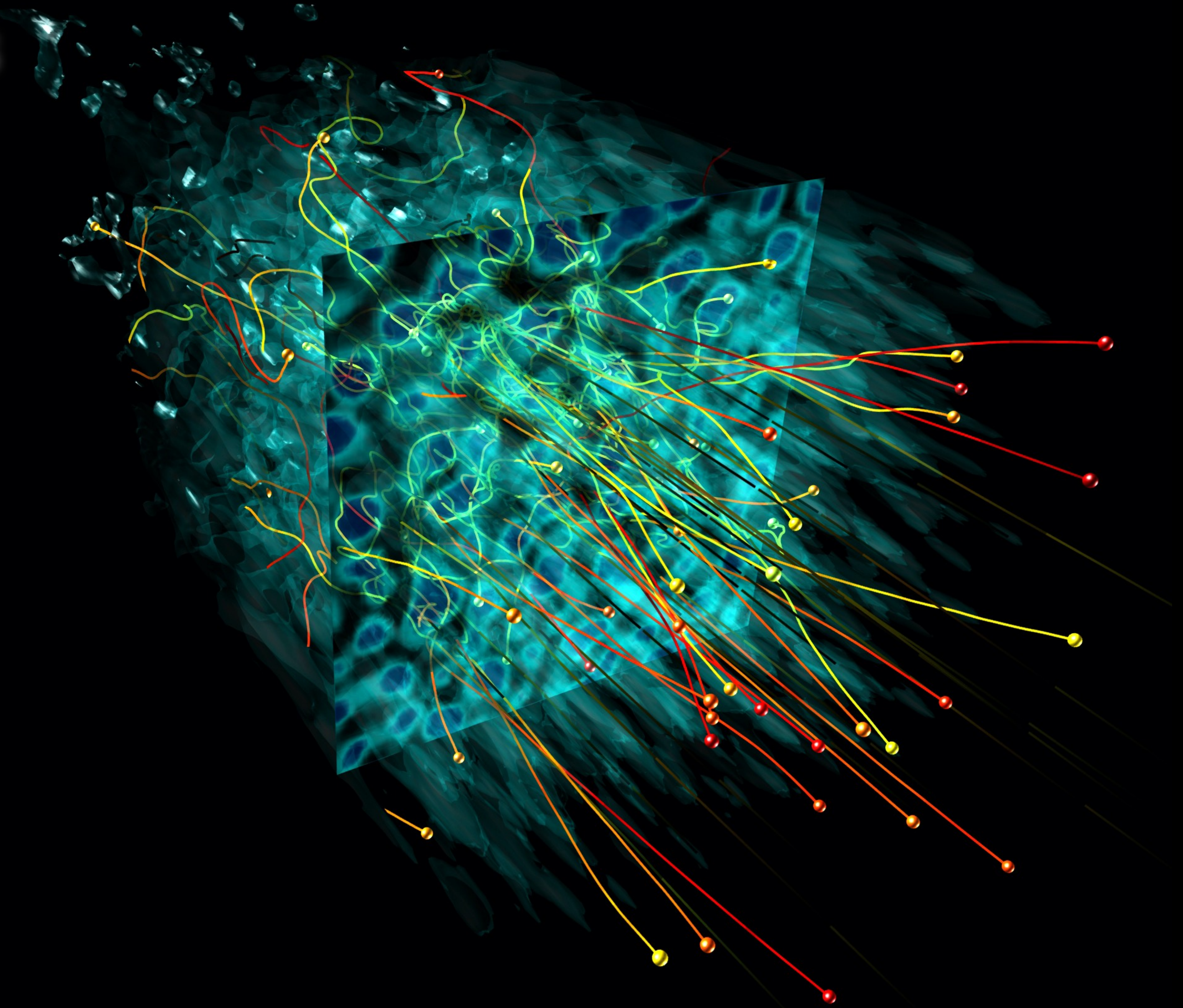
Shock transition typically defined by ion Larmor radius



Electrons need to be pre-accelerated to start crossing the shock front

Particle injection is determined by microscopic plasma processes and is not well understood!

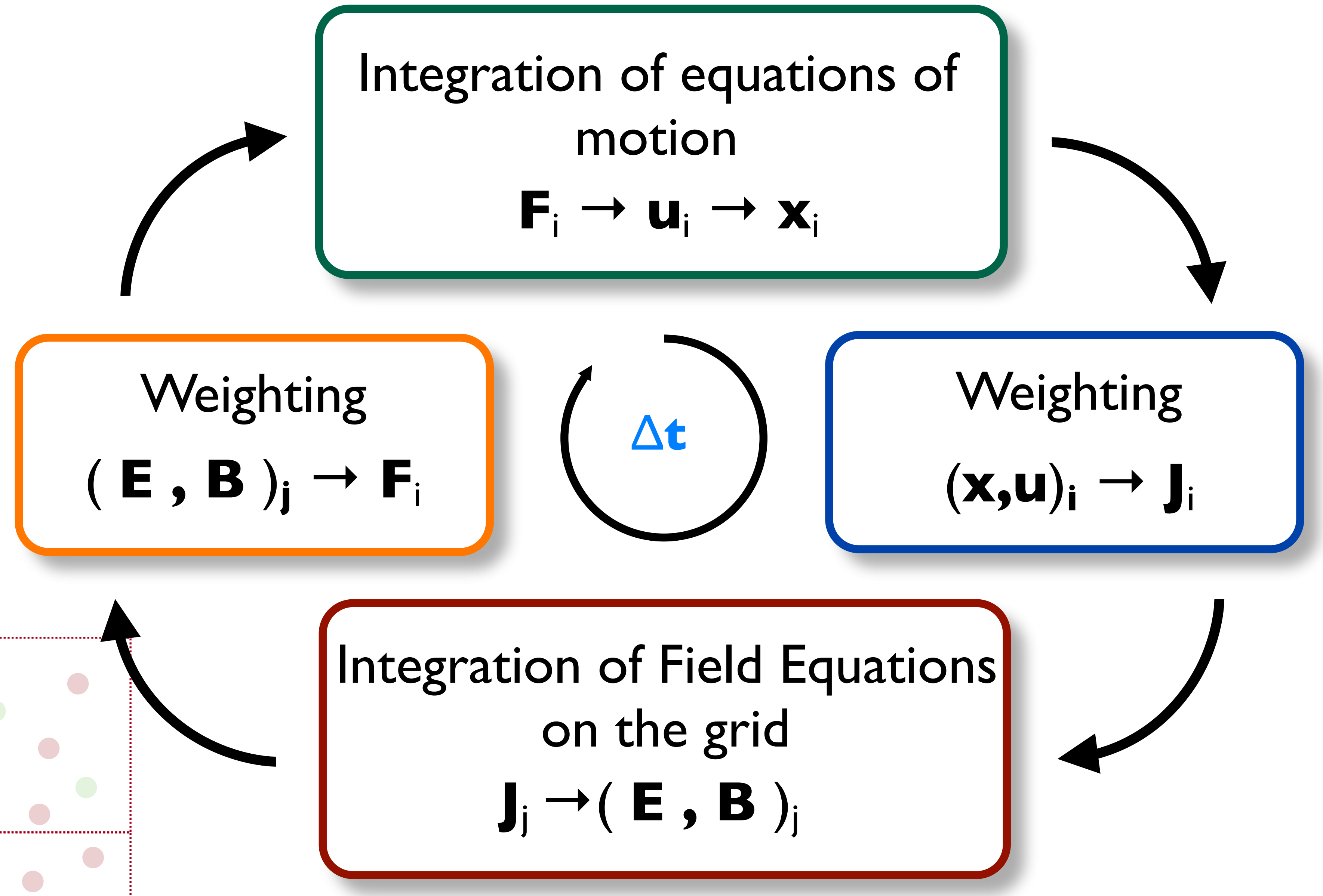
Kinetic simulations reveal rich shock microphysics

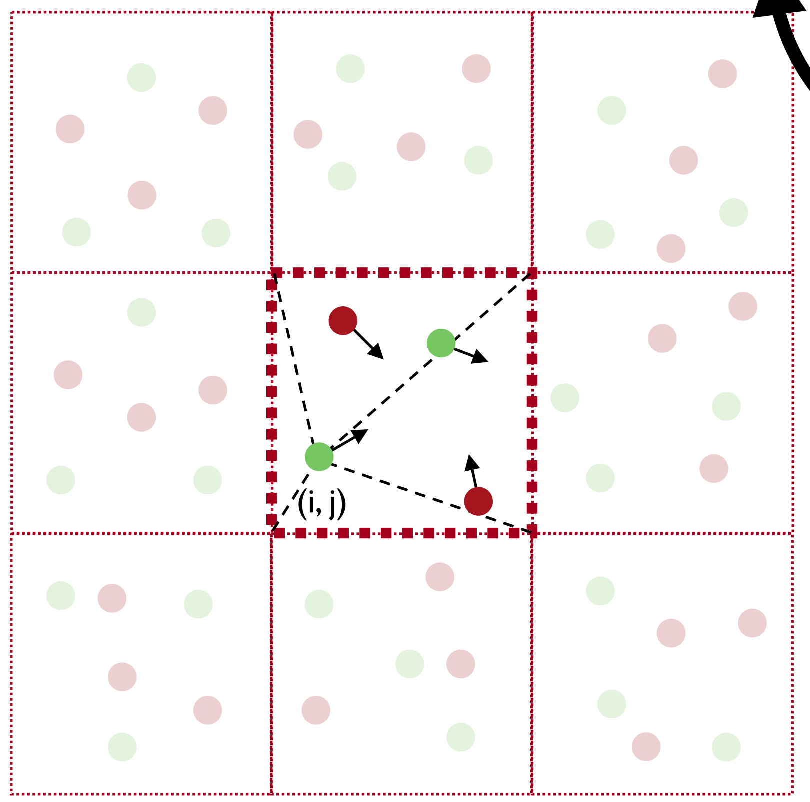


Kinetic simulations are critical to unveil microphysics of shocks

Particle-in-cell (PIC) kinetic plasma simulations

$$\frac{d\mathbf{u}}{dt} = \frac{q}{m}\left(\mathbf{E} + \frac{1}{\gamma c}\mathbf{u}\times\mathbf{B}\right)$$

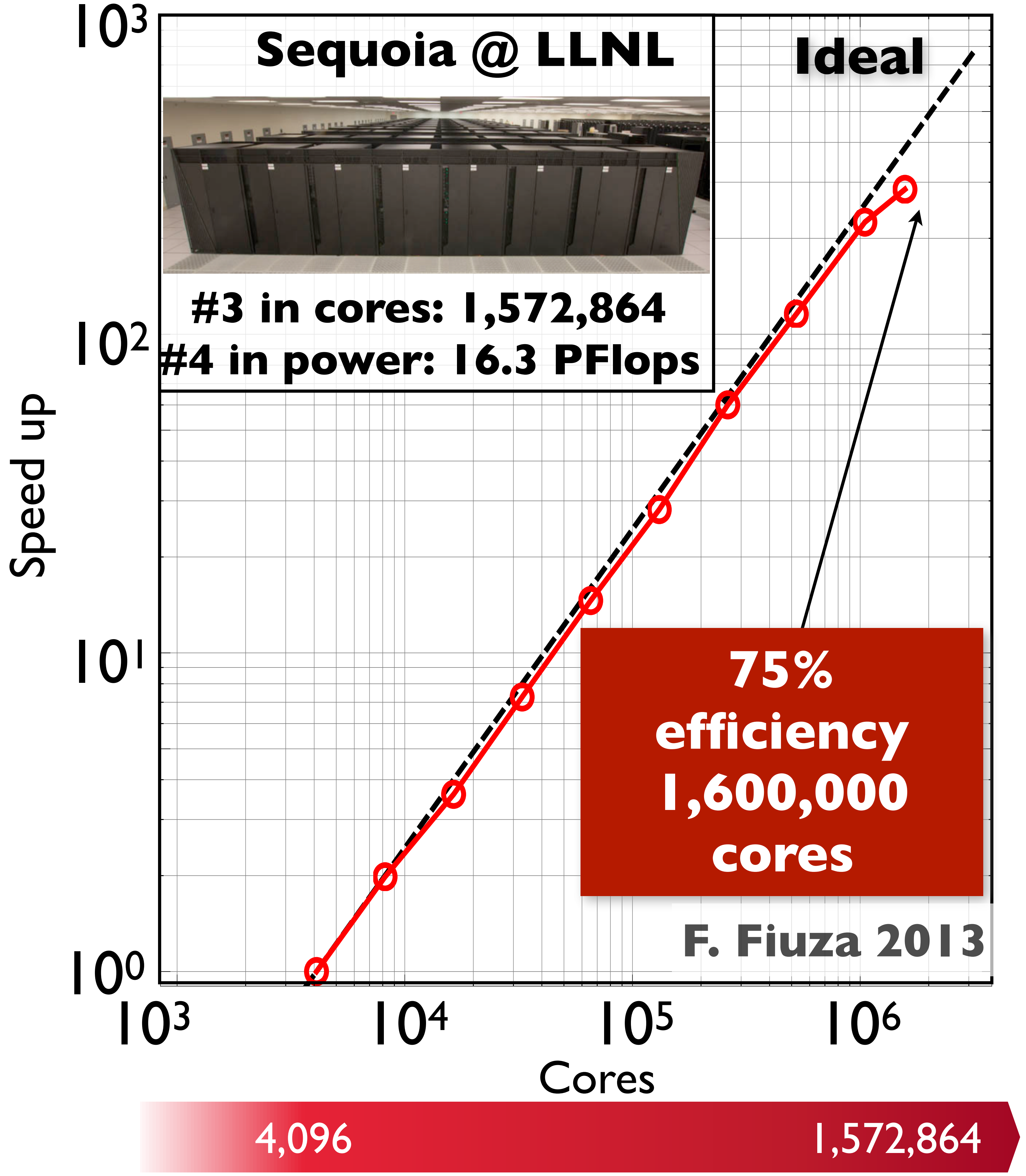




$$\frac{\partial \mathbf{E}}{\partial t} = c\vec{\nabla}\times\mathbf{B} - 4\pi\mathbf{j}$$

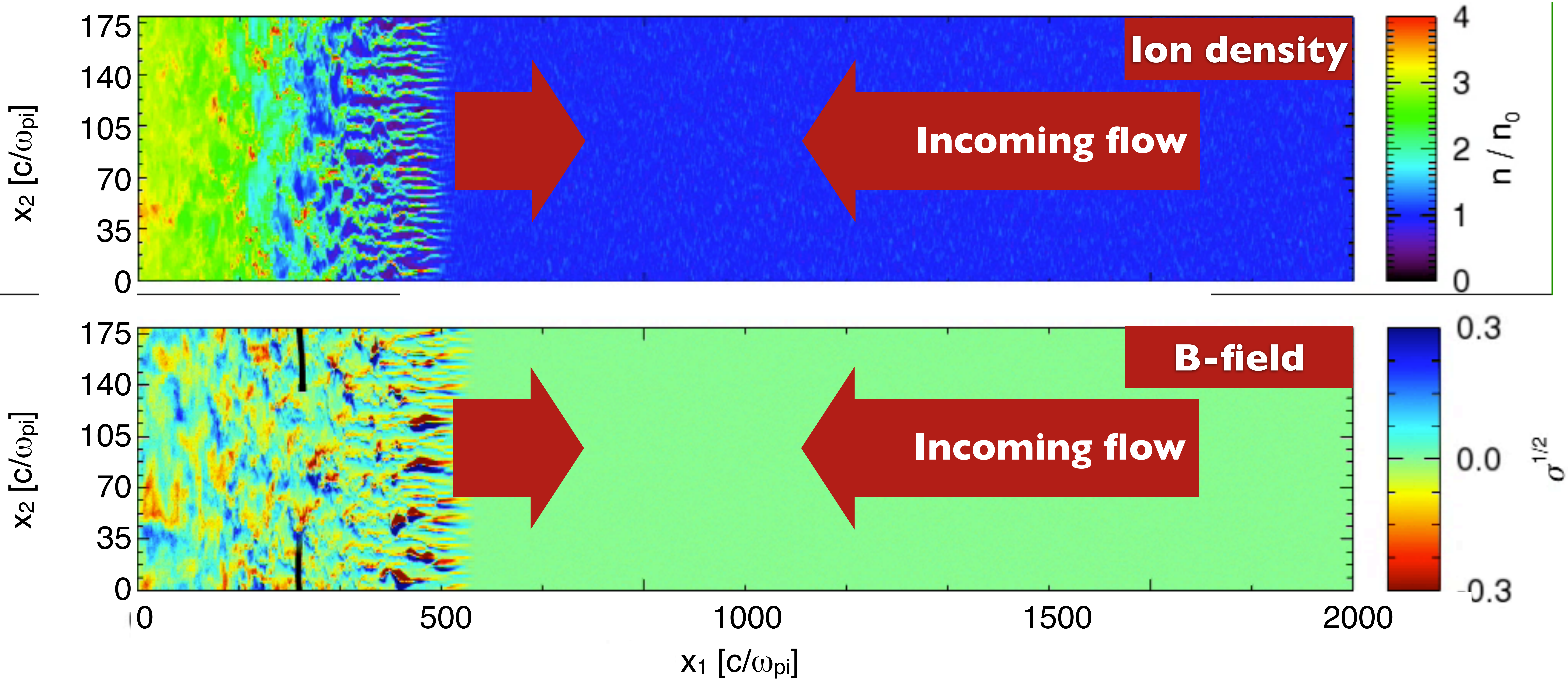
$$\frac{\partial \mathbf{B}}{\partial t} = -c\vec{\nabla}\times\mathbf{E}$$

Strong scaling of OSIRIS PIC code (IST/UCLA)



Dawson, Buneman, 1960's; Birdsall and Langdon, 1985

Formation of collisionless shocks in weakly magnetized plasmas



Can small-scale fields lead to efficient electron injection?

Weibel instability can amplify B-fields in weakly magnetized plasmas

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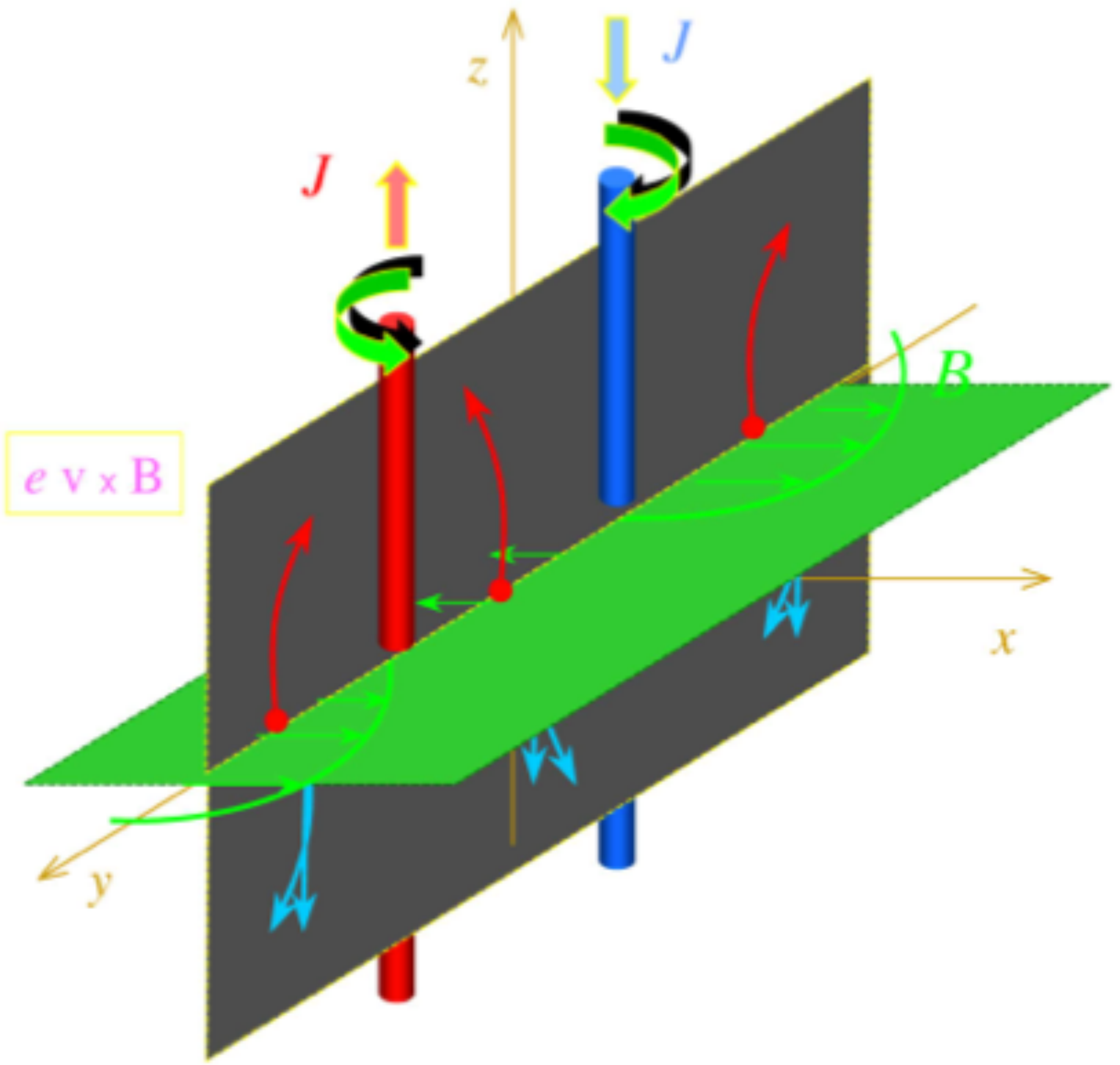
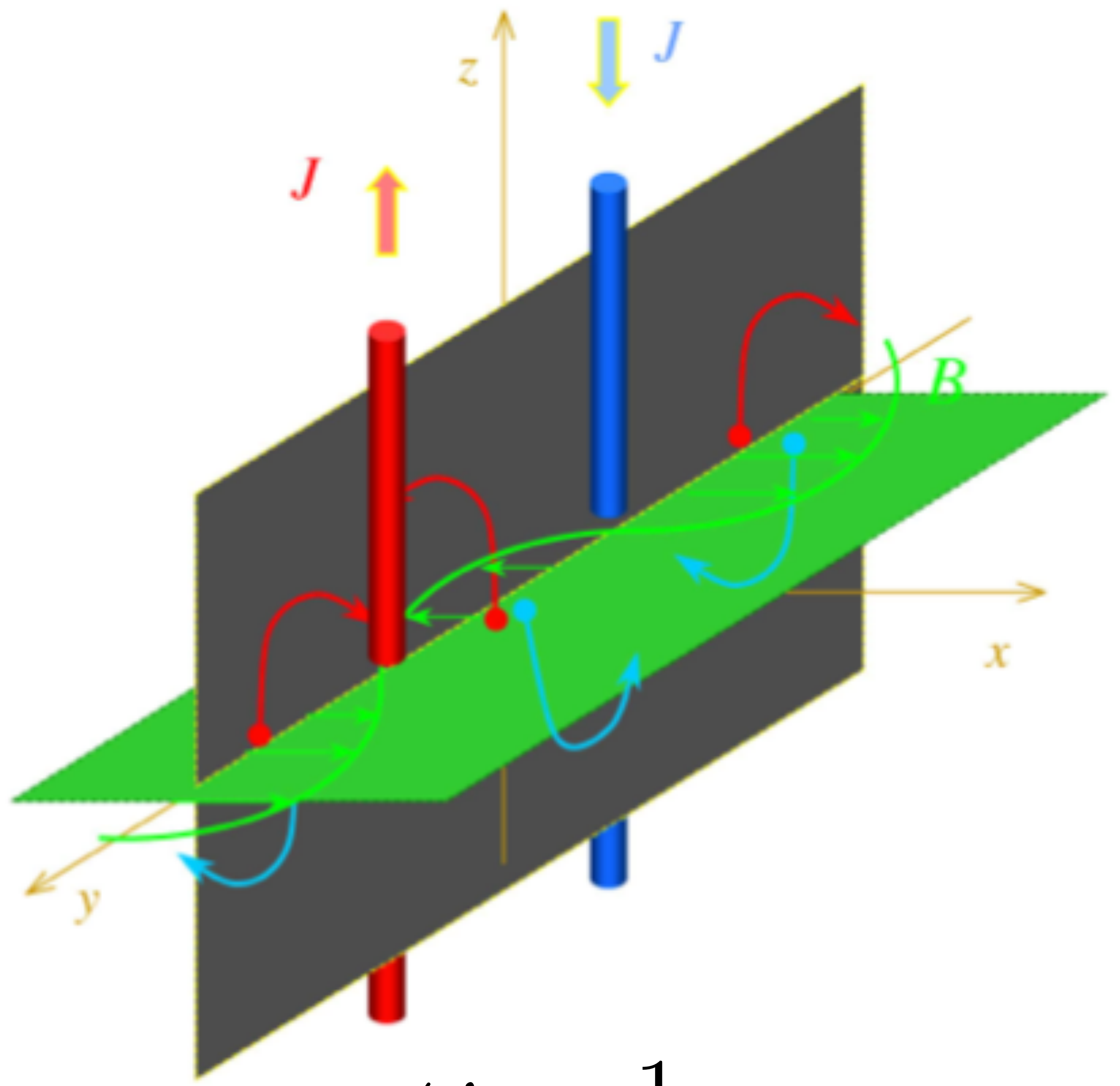
Linear regime



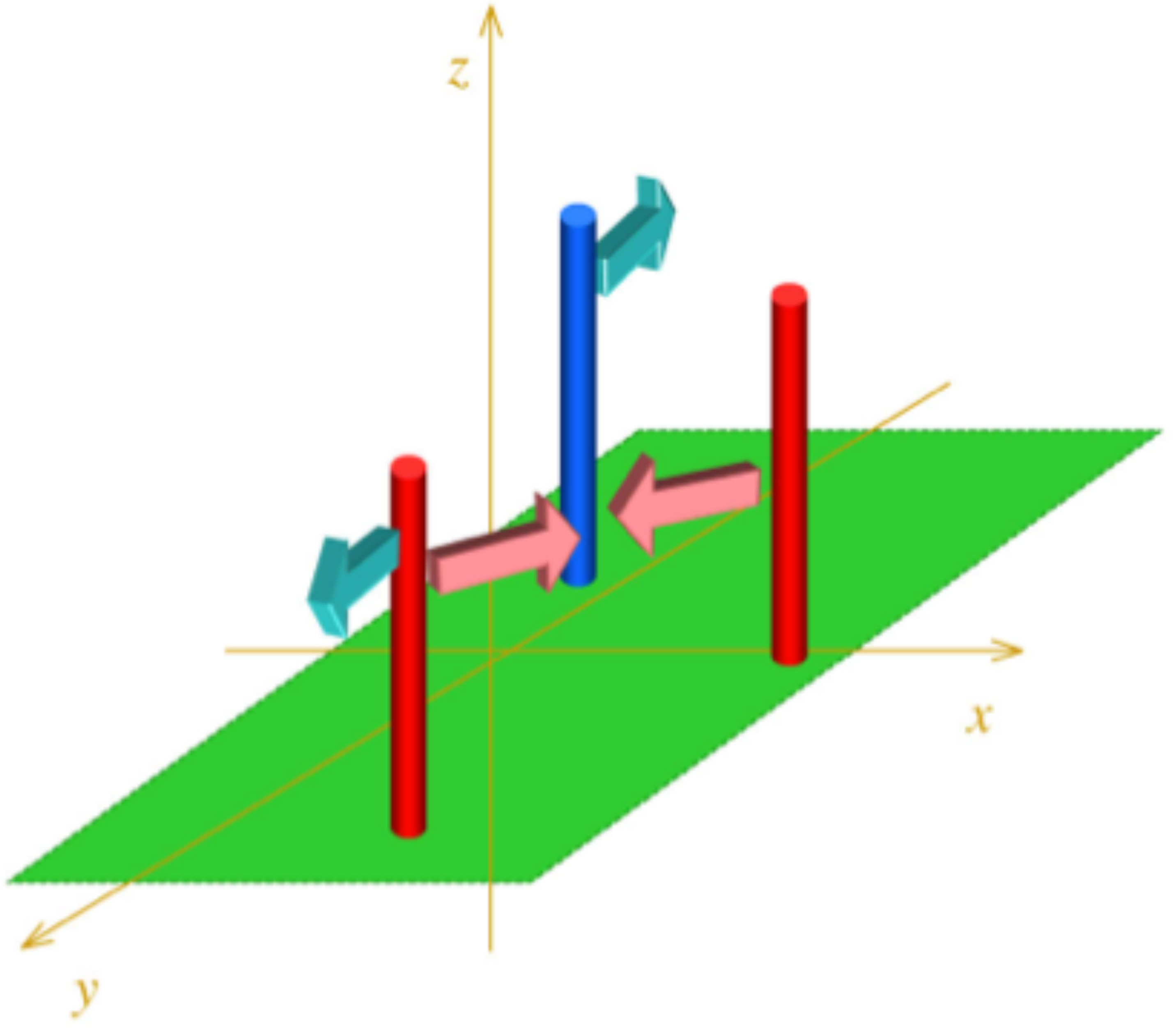
$$\Gamma_W = \frac{v_0}{c}\frac{\omega_{pi}}{\gamma_0^{1/2}}$$

Saturation



$$k_{max} = \frac{\omega_{pi}}{c}\frac{1}{\gamma_0^{1/2}}$$

Non-linear regime

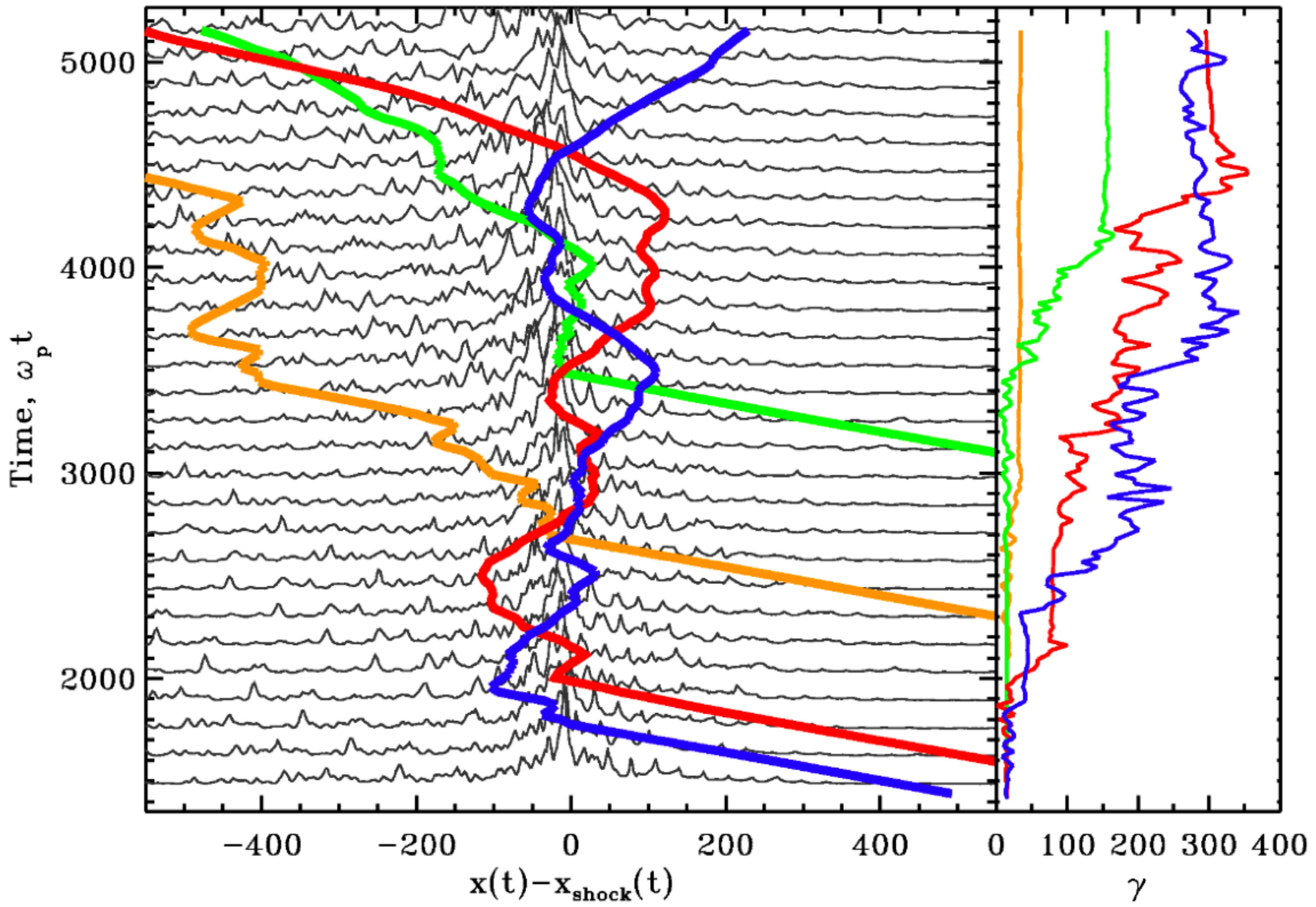


Instability can transfer ~10% of kinetic energy of plasma flows into magnetic energy

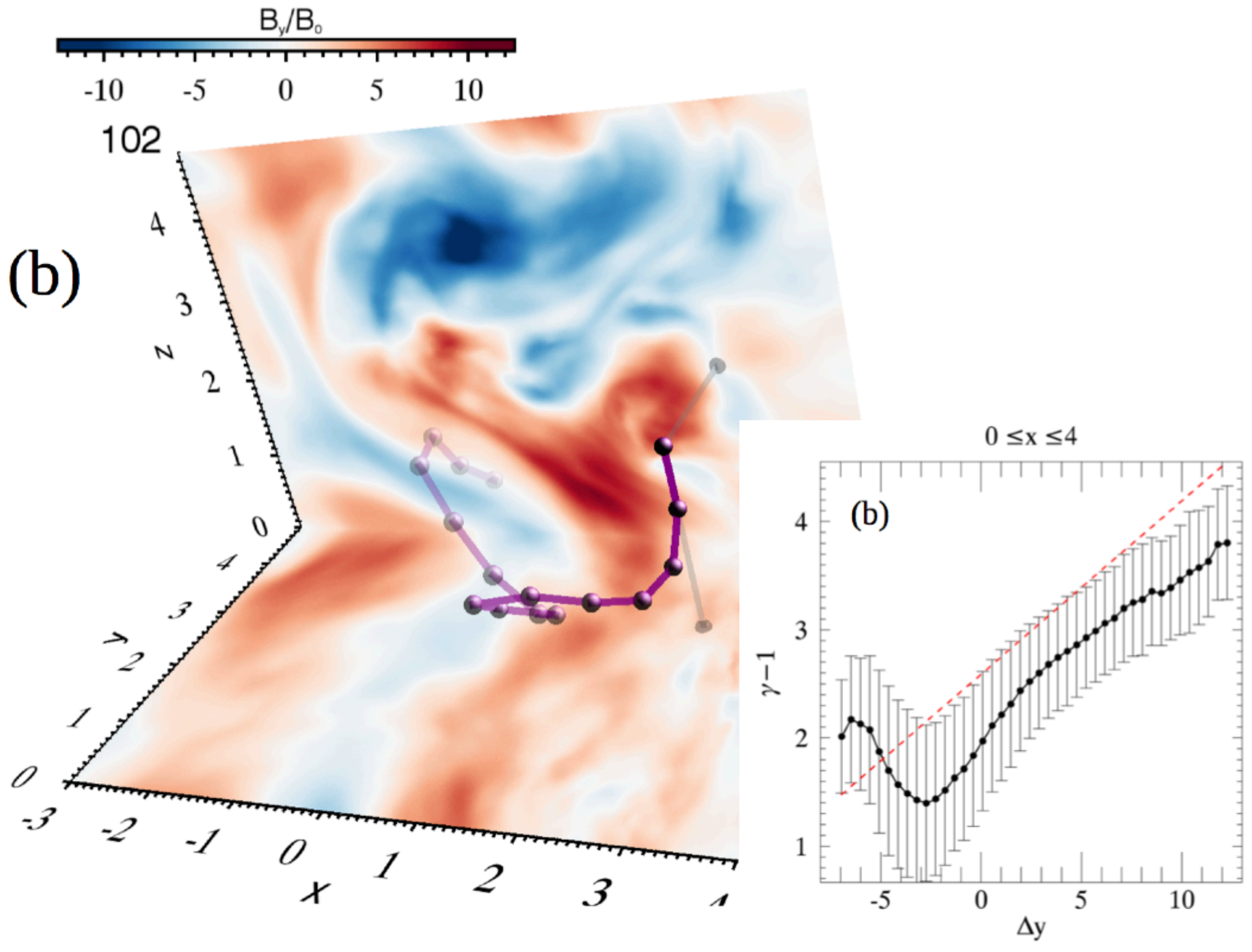
E. S. Weibel, PRL 2, 83 (1959); B. D. Fried, Phys. Fluids 2, 337 (1959)
A. Gruzinov & E. Waxman, APJ 511, 852 (1999); M. Medvedev & A. Loeb, ApJ 526, 697 (1999)

Different injection mechanisms are likely to operate at different plasma conditions

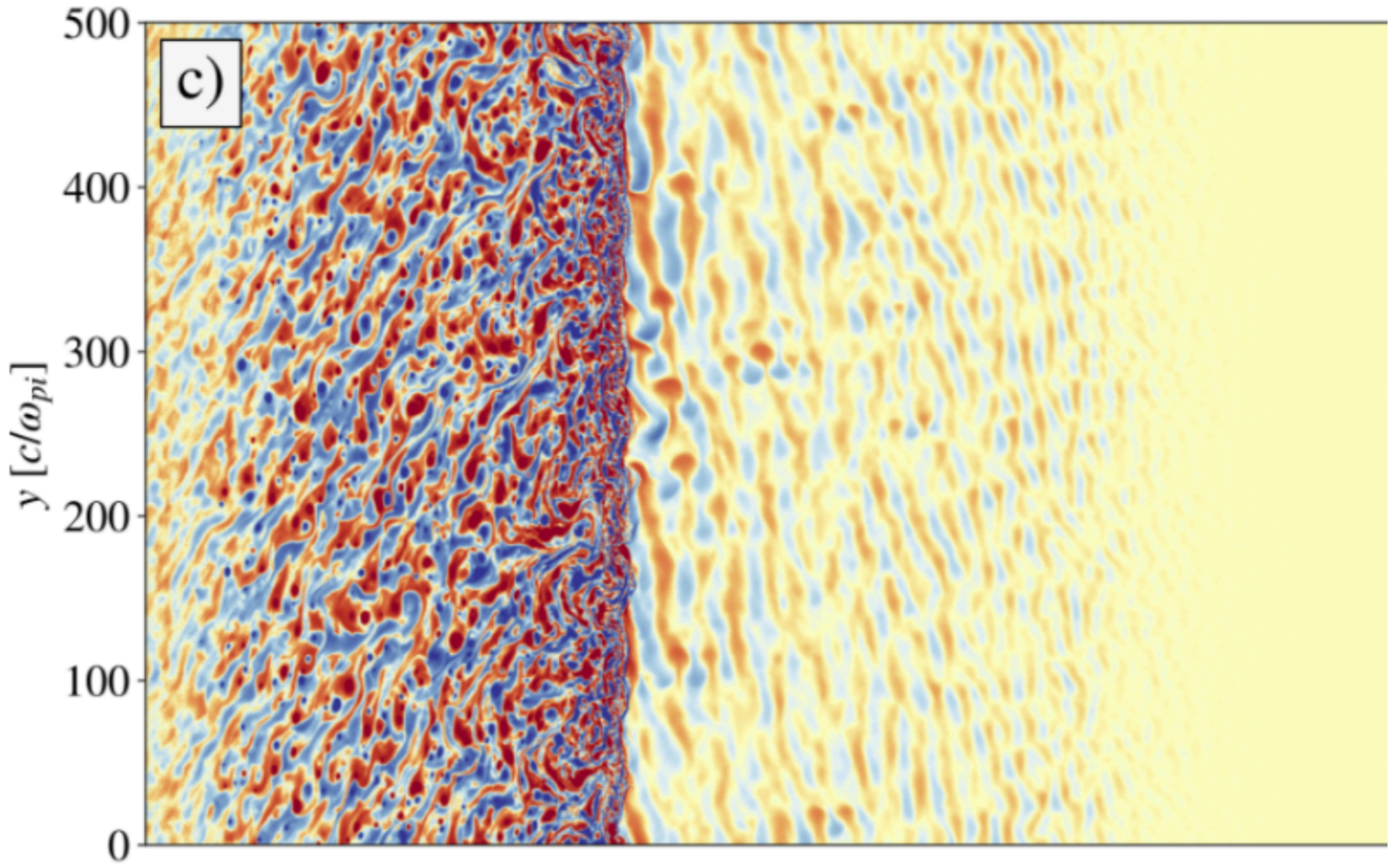
Acceleration in relativistic Weibel shocks [1]



Stochastic SDA in Weibel turbulence in perpendicular shocks [2]



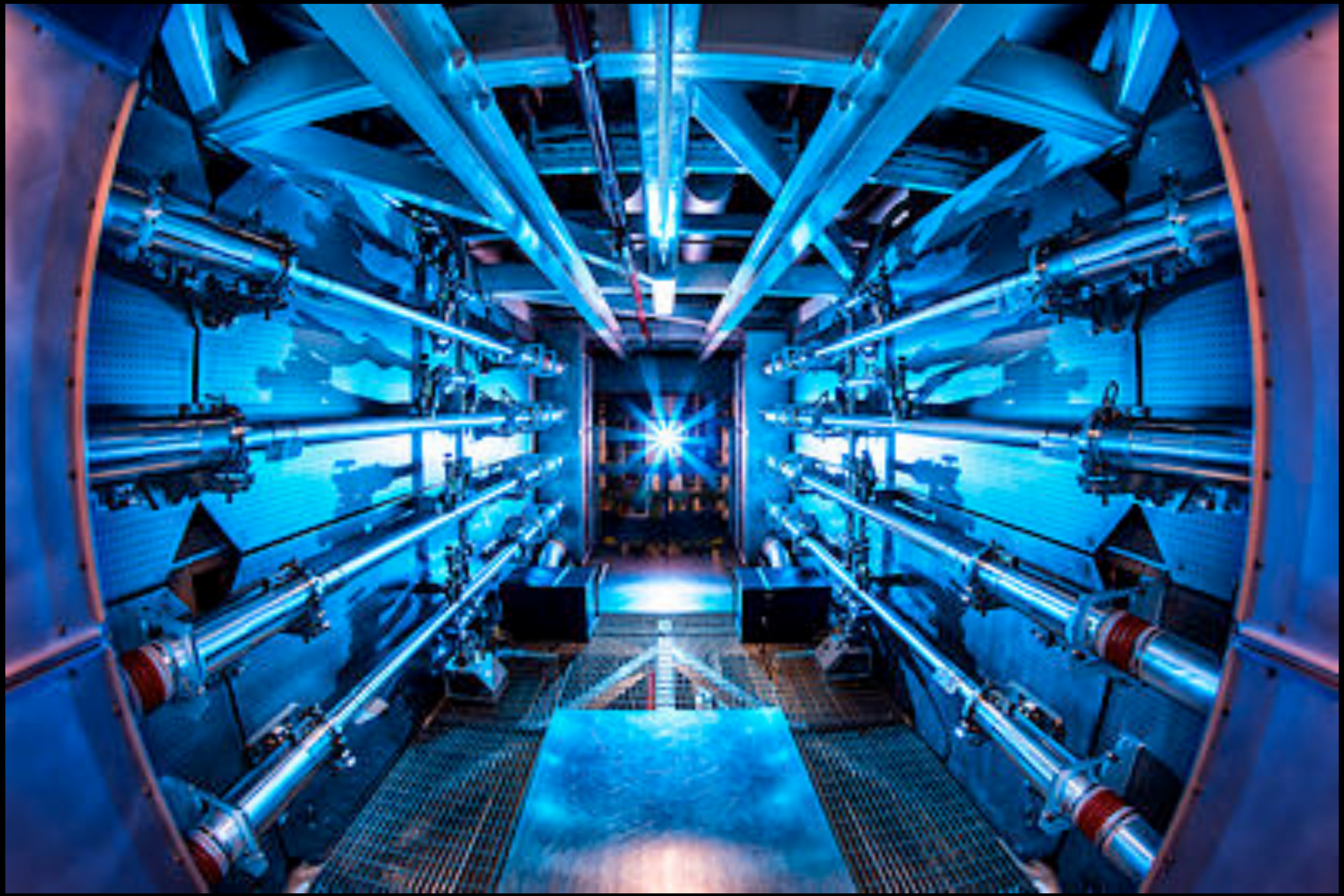
Injection by Bell waves in parallel shocks [3]



Depending on the shock Mach number and ambient magnetic field orientation a large range of plasma instabilities can control magnetic field amplification (Weibel, Buneman, Bell, …)

[1] Spitkovsky ApJL 2008
[2] Matsumoto et al. PRL 2017
[3] P. Crumley et al., MNRAS 2019

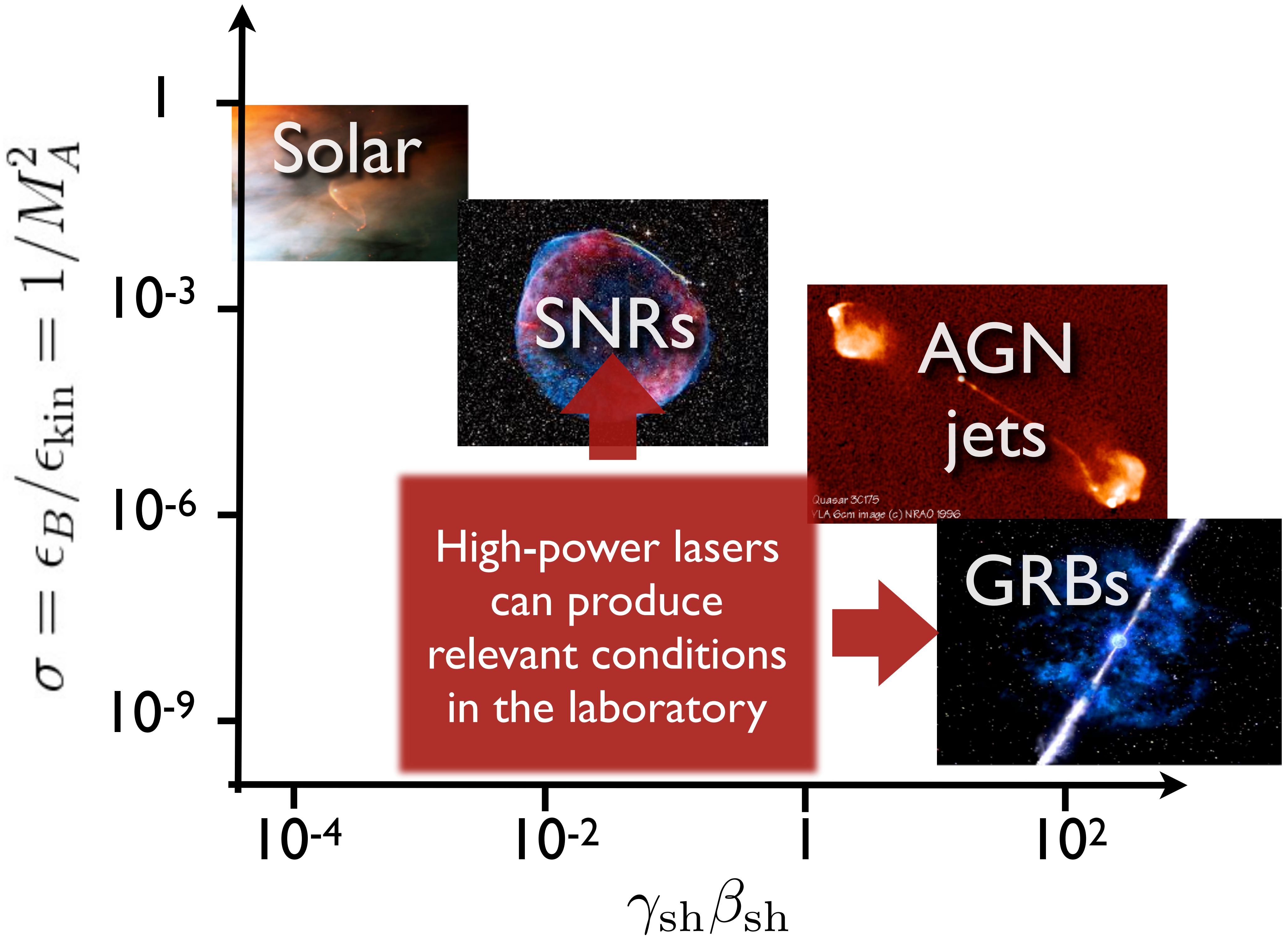
Can laboratory experiments help validate shock microphysics models?

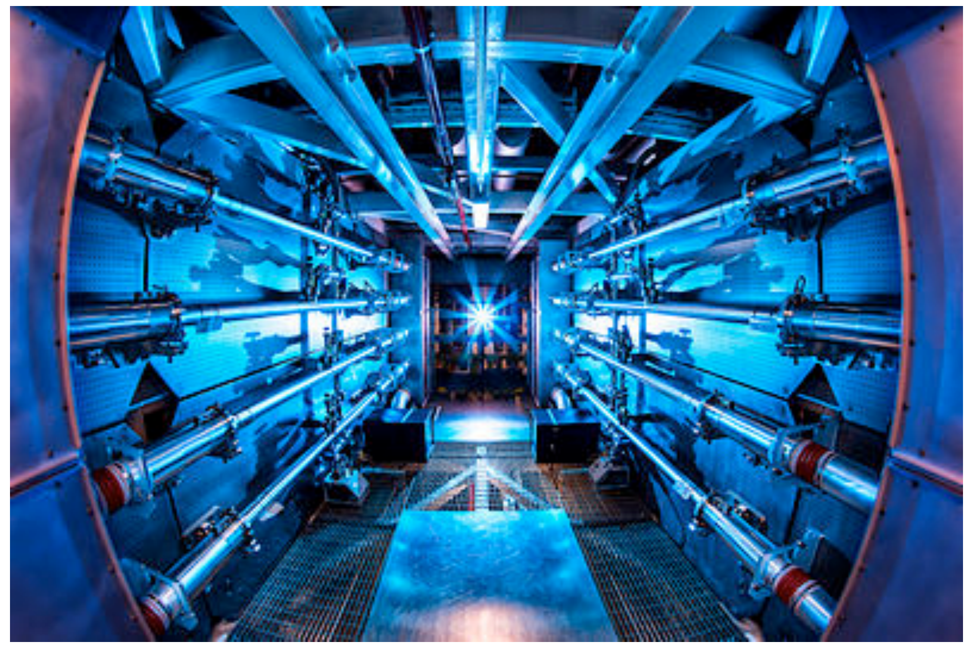


National Ignition Facility @ LLNL

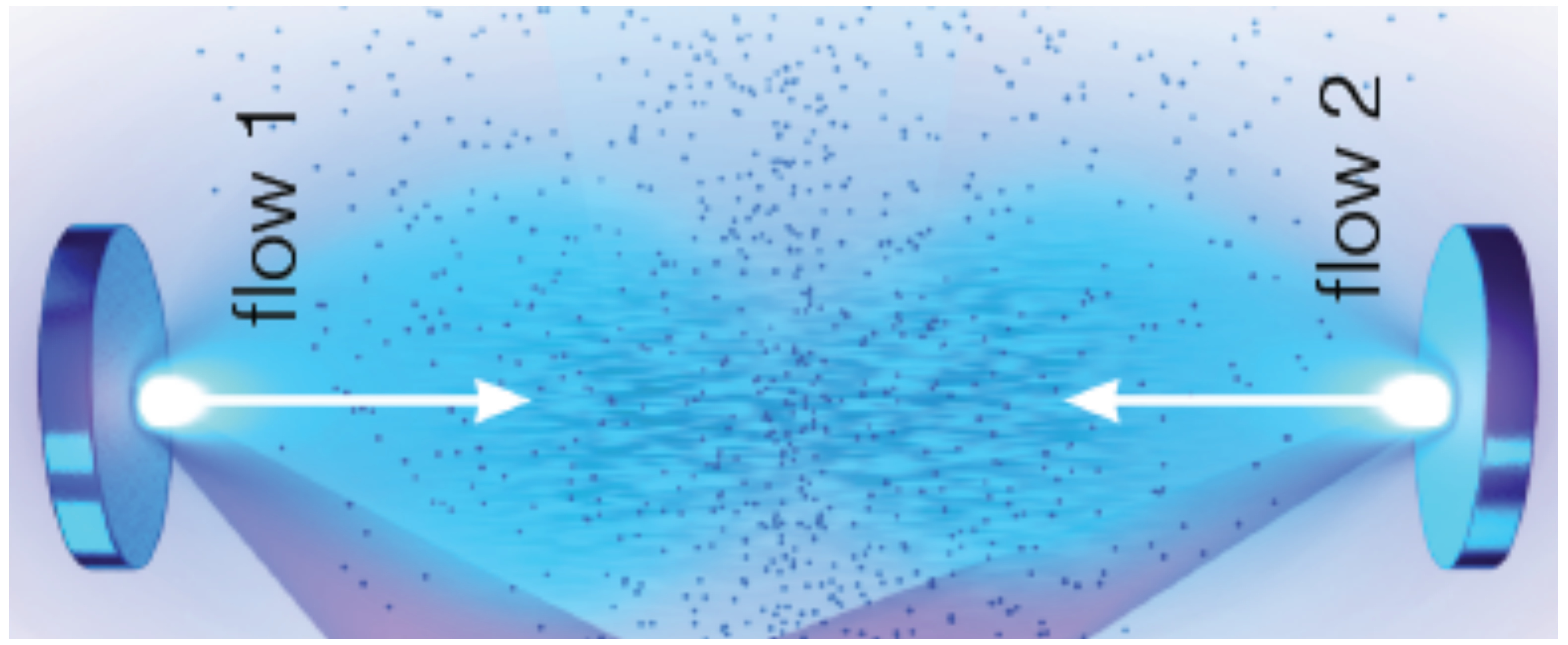
Laboratory experiments can greatly complement studies of particle acceleration

- Experimental studies of ion-acoustic shocks since 60s
- Only now it is becoming possible to drive energetic enough plasma flows with lasers to produce electromagnetic shocks (L_{system} > 100 c/ω_{pi} and λ_{mfp} >> L_{system})
- Controlled study of shock structure and particle acceleration for different plasma conditions (including high M_A)
- Benchmark numerical tools that are being used to develop particle acceleration models (e.g. PIC and hybrid)





National Ignition Facility



Cartoon of laser-driven counter-streaming plasma experiments

Shock microphysics can be scaled from lab to astrophysical plasmas

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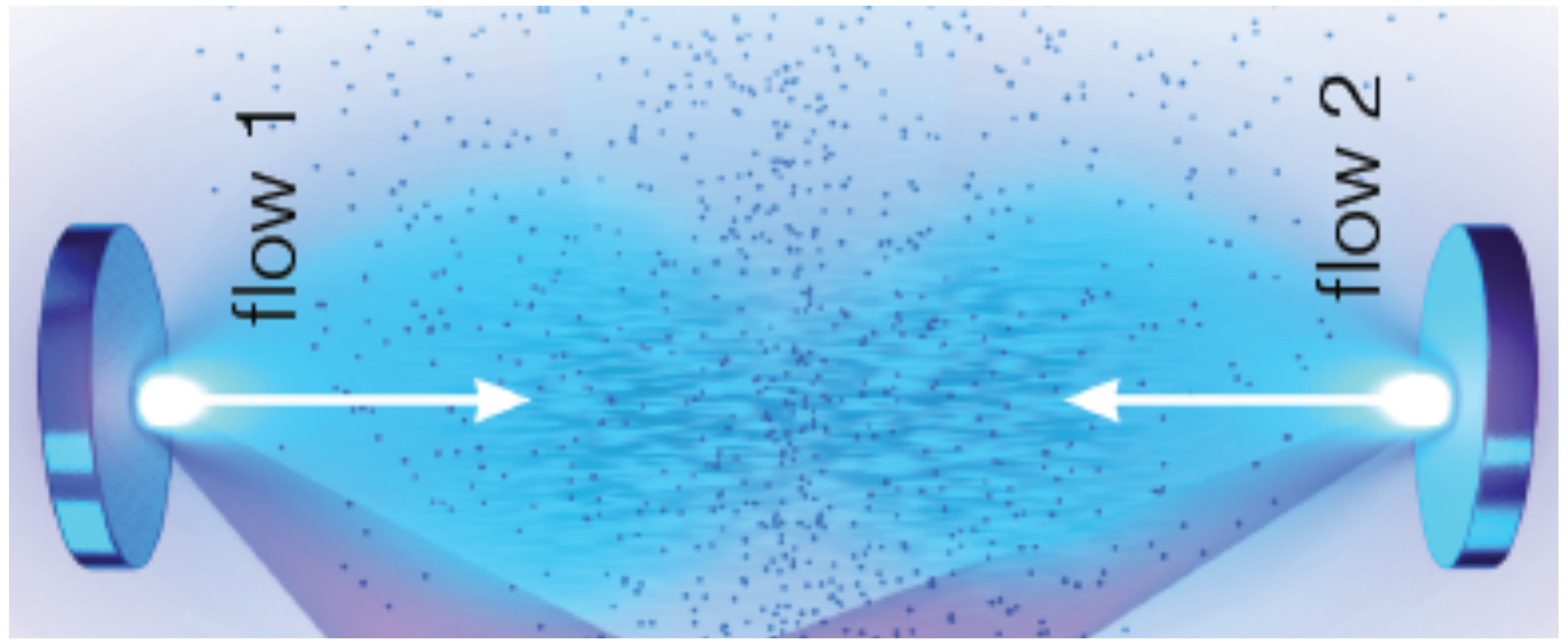
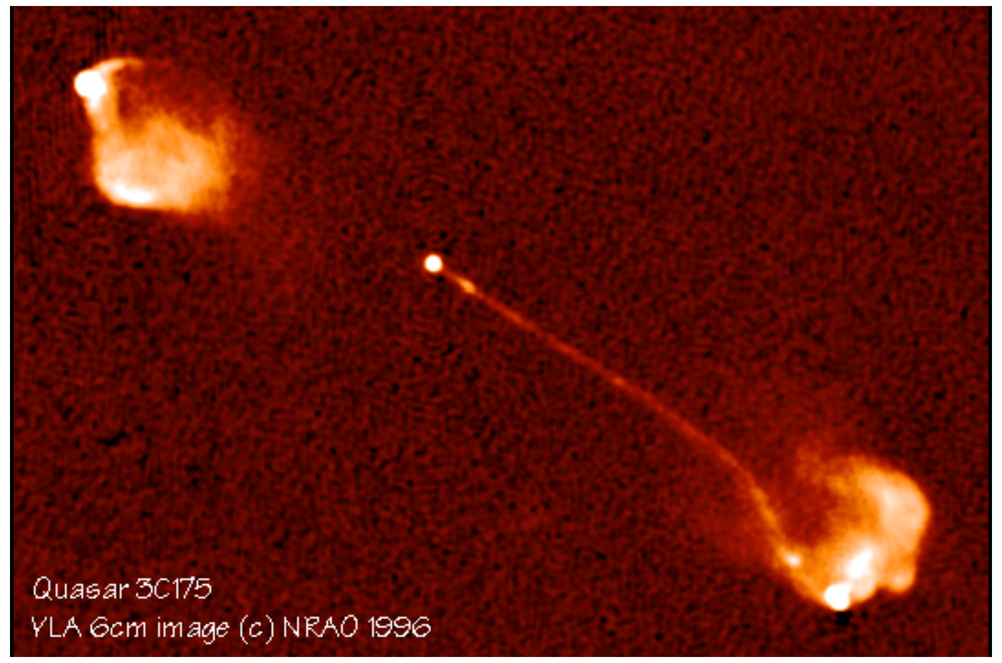
Laboratory system 1



Astrophysical system 2



Main assumptions: collisionless system ($\lambda_{mfp} >> L_{system}$), weakly magnetized ($\sigma << 1$), $v_{flow} >> v_{th}$, electromagnetic instabilities are dominant (Div. E ~ 0)

Normalized Vlasov-Maxwell equations:

$$\frac{\partial f_i'}{\partial t'} + \boldsymbol{v}' \cdot \frac{\partial f_i'}{\partial \boldsymbol{r}'} + \left(-\frac{\partial \boldsymbol{A}'}{\partial t'} + \boldsymbol{v}' \times \nabla' \times \boldsymbol{A}'\right) \cdot \frac{\partial f_i'}{\partial \boldsymbol{v}'} = 0,$$

$$\frac{\partial f_e'}{\partial t'} + \boldsymbol{v}' \cdot \frac{\partial f_e'}{\partial \boldsymbol{r}'} + \frac{1}{\mu}\left(-\frac{\partial \boldsymbol{A}'}{\partial t'} + \boldsymbol{v}' \times \nabla' \times \boldsymbol{A}'\right) \cdot \frac{\partial f_e'}{\partial \boldsymbol{v}'} = 0$$

$$\nabla'^2 \boldsymbol{A}' = \left(\int f_e' \boldsymbol{v}' \, d^3\boldsymbol{v}' - \int f_i' \boldsymbol{v}' \, d\boldsymbol{v}'^3\right). \qquad \mu \equiv \frac{Zm_e}{Am_p}$$

Scaling relations between both systems:

$$L_2 = L_1 \sqrt{\frac{n_1}{n_2}} \qquad t_2 = t_1 \frac{u_1}{u_2}\sqrt{\frac{n_1}{n_2}} \qquad T_{i2} = \frac{A_2 u_2^2}{A_1 u_1^2} T_{i1}$$

$$\tilde{E}_2 = \tilde{E}_1 \frac{u_2^2}{u_1^2}\sqrt{\frac{n_2}{n_1}} \qquad \tilde{B}_2 = \tilde{B}_1 \frac{u_2}{u_1}\sqrt{\frac{n_2}{n_1}}$$

D. D. Ryutov et al. Plasma Phys. Control. Fusion 54, 105021 (2012)

High Mach # plasma flows can be created in the lab by laser irradiation

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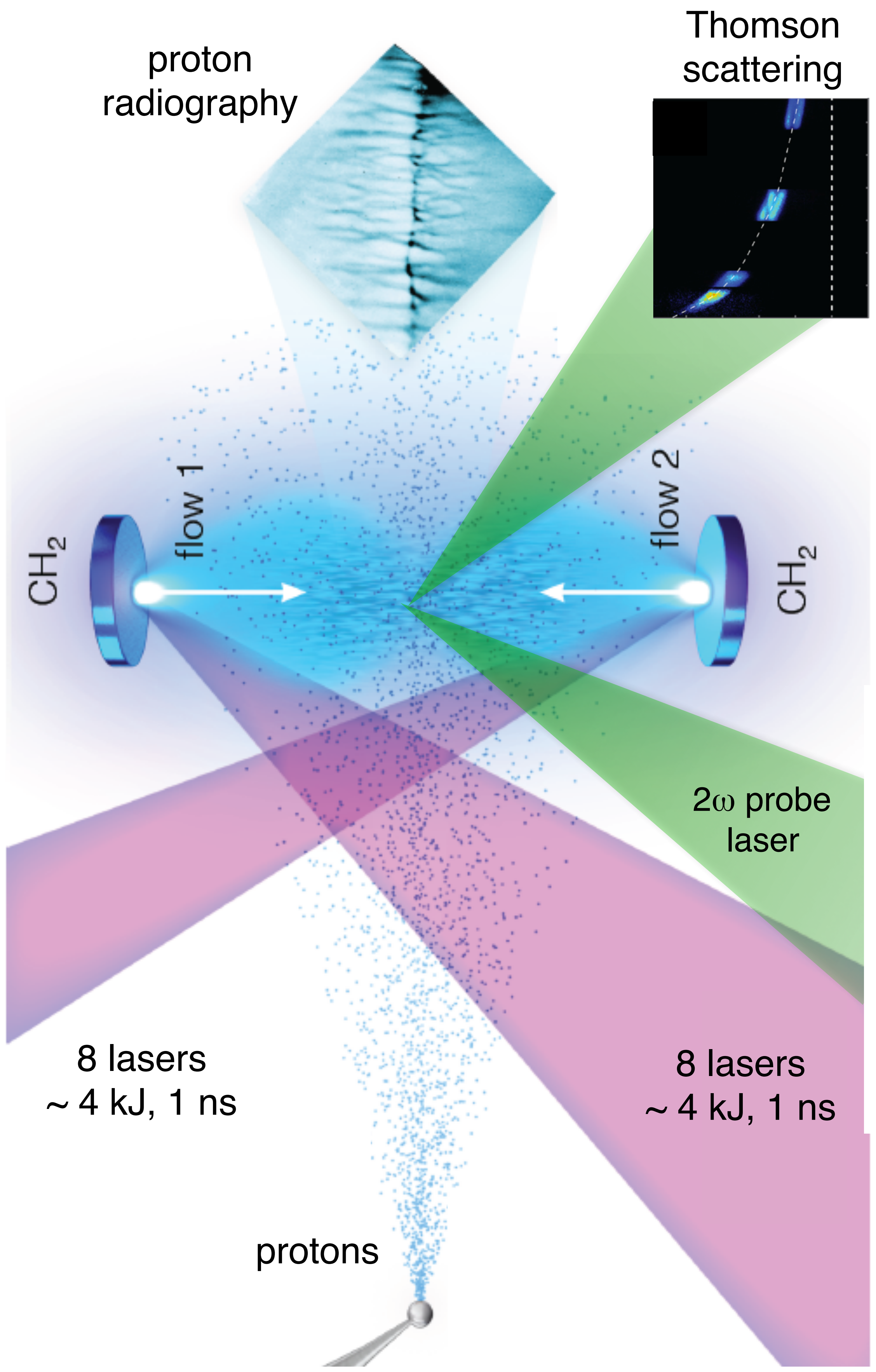
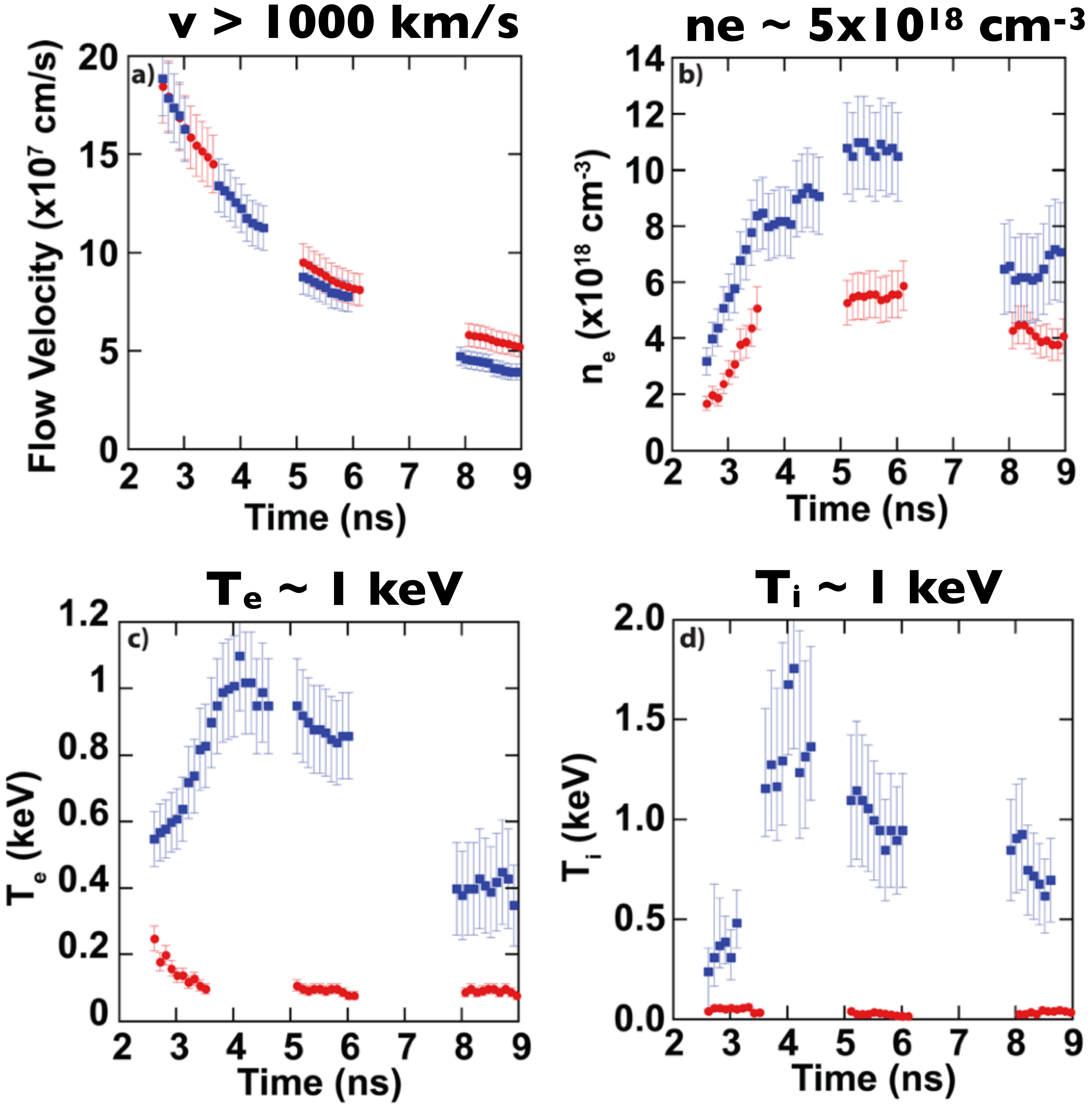
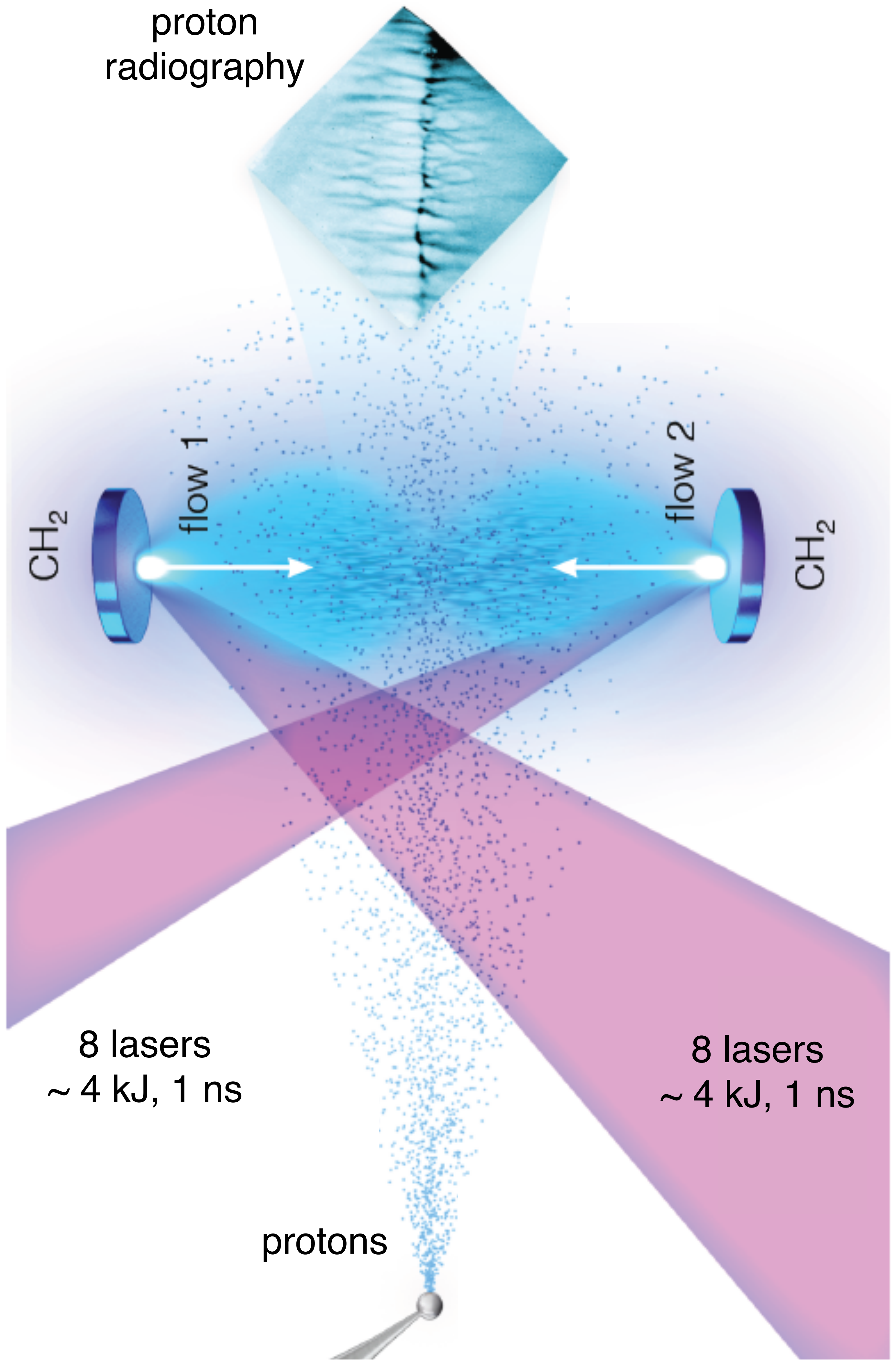


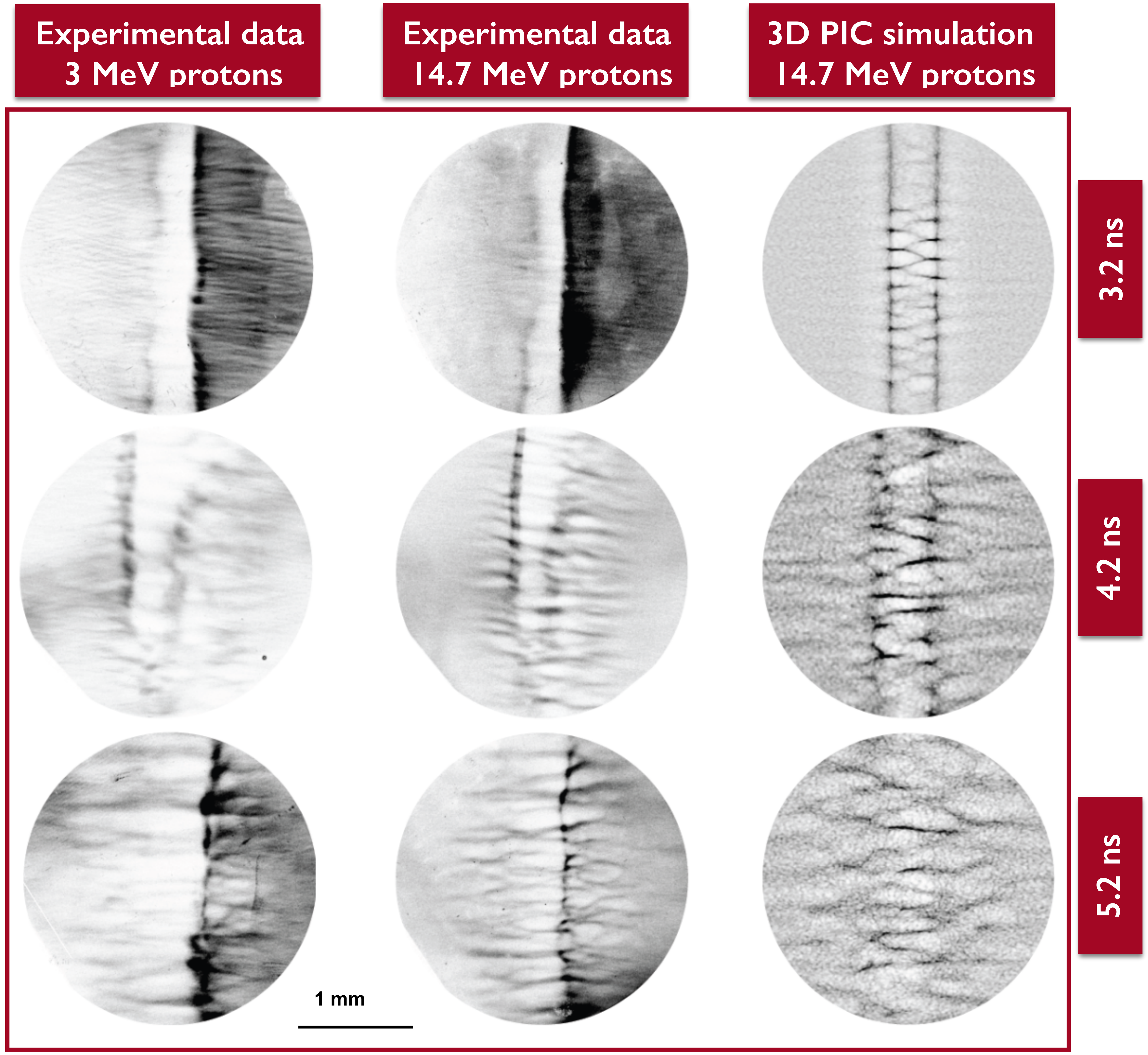


Collisionless interaction with λ_{mfp} > 10 L_{system}

S. Ross et al., Phys. Plasmas (2012)

B-field amplification by the ion Weibel instability observed





Relative proton deflection at 3 MeV vs. 14.7 MeV indicates B-field dominate over E-field

C. Huntington, F. Fiuza *et al*. Nat. Physics 11, 173 (2015)

First measurements of local current structure and saturation level

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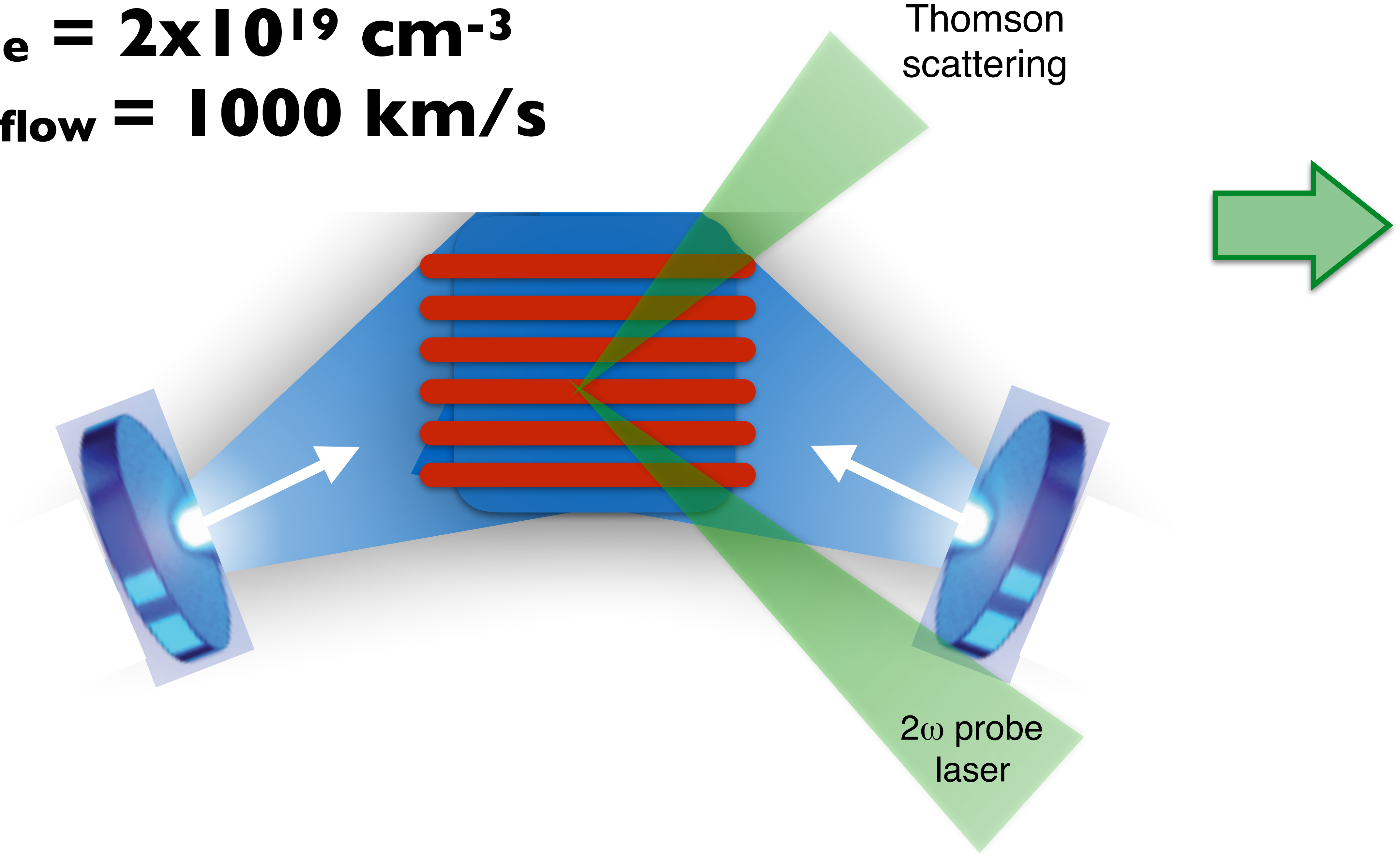
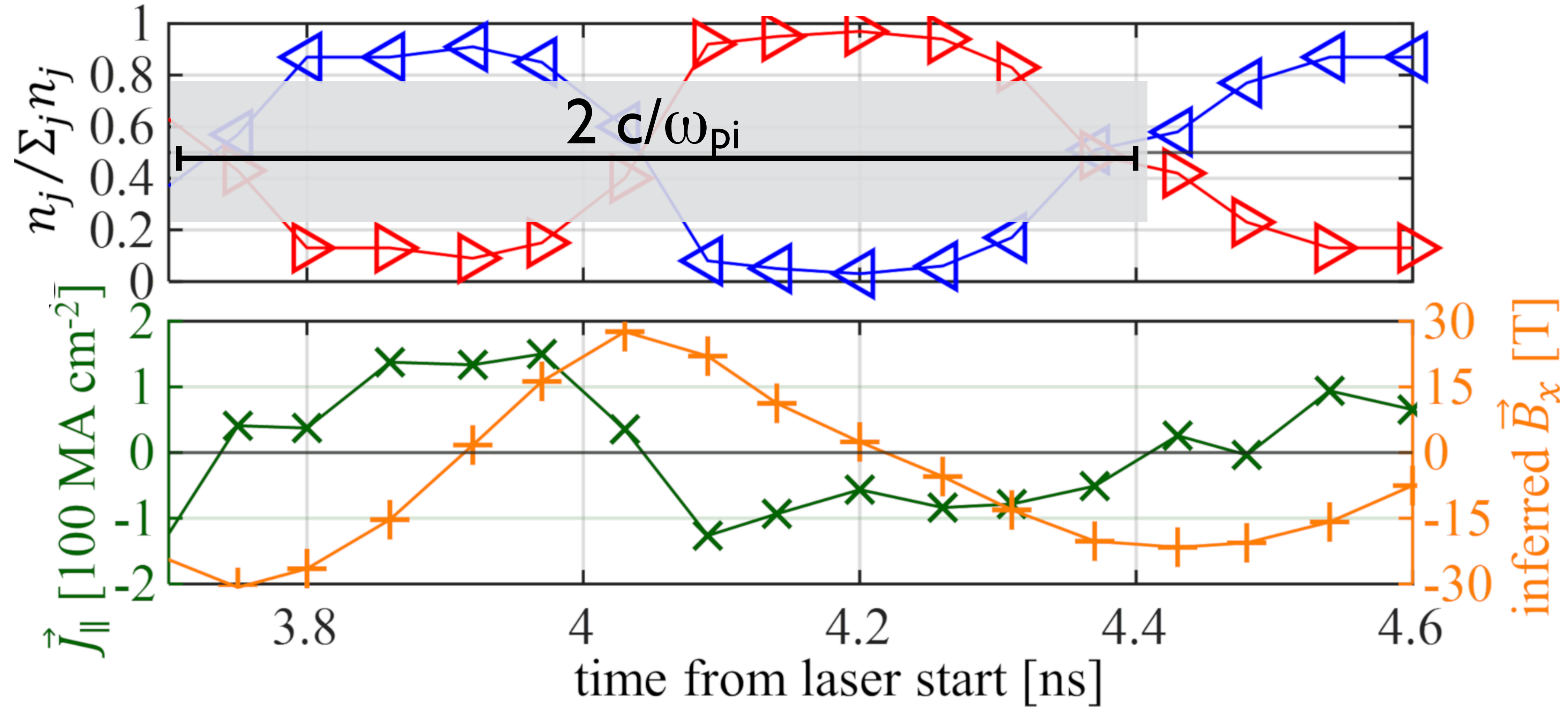
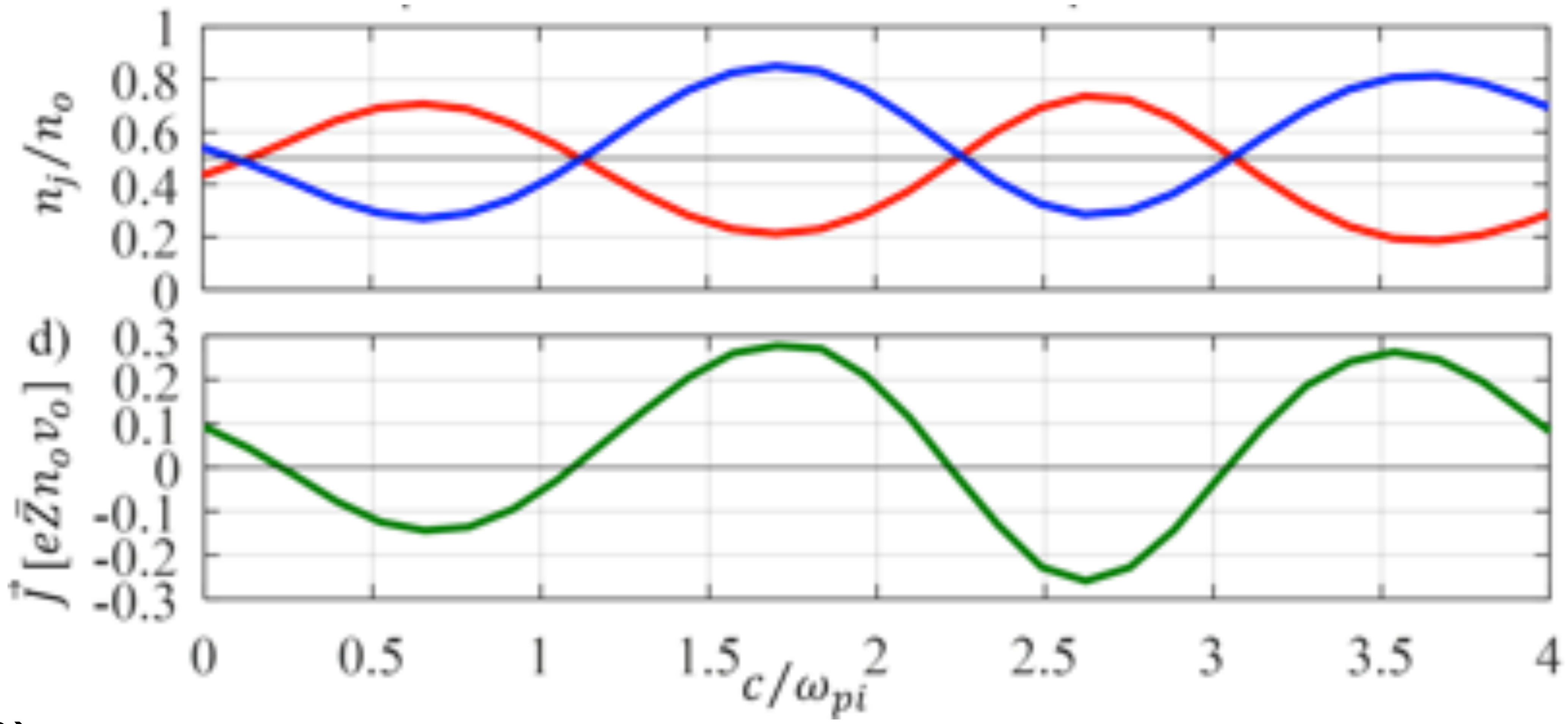
n_e = 2x10^{19} cm^{-3}
v_{flow} = 1000 km/s



Experiments



3D simulations



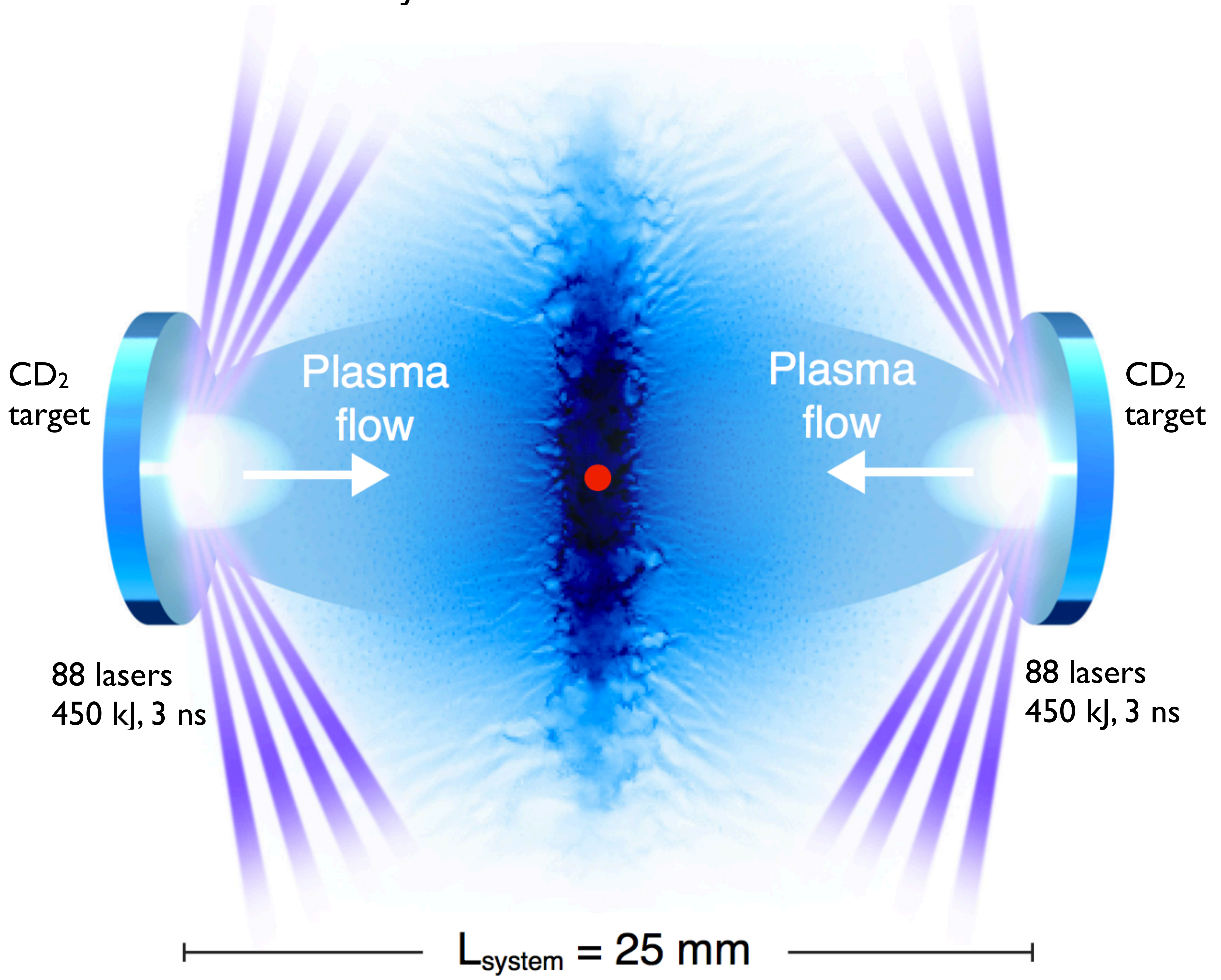
Measured B-field = 30 T corresponds to $\sigma = \varepsilon_B/\varepsilon_{kin} \sim 0.01$

Saturation amplitude consistent with magnetic trapping mechanism [Davidson 1972] (not with the Alfven limit)

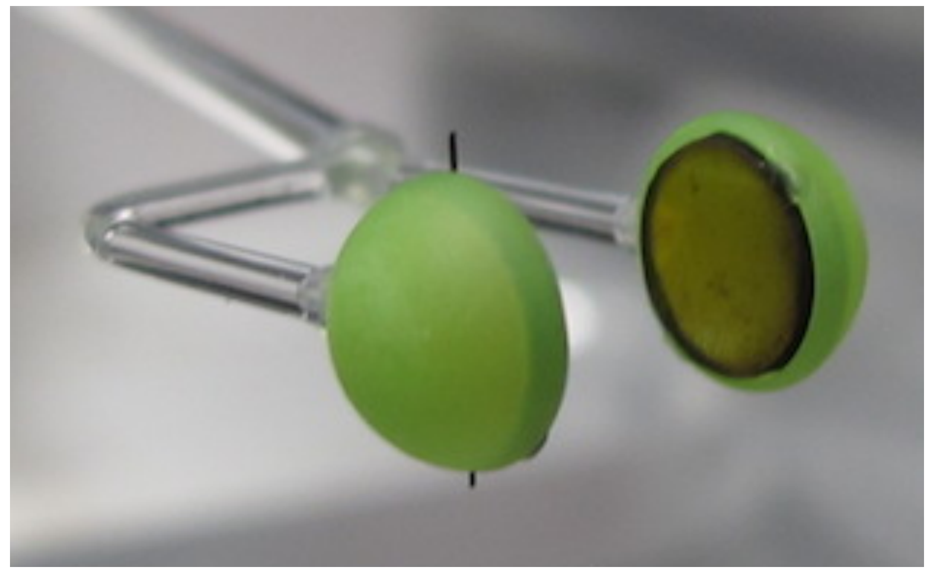
G. Swadling, C. Bruulsema, F. Fiuza et al., PRL 124, 215001 (2020)

Platform to study shock formation and particle acceleration at NIF

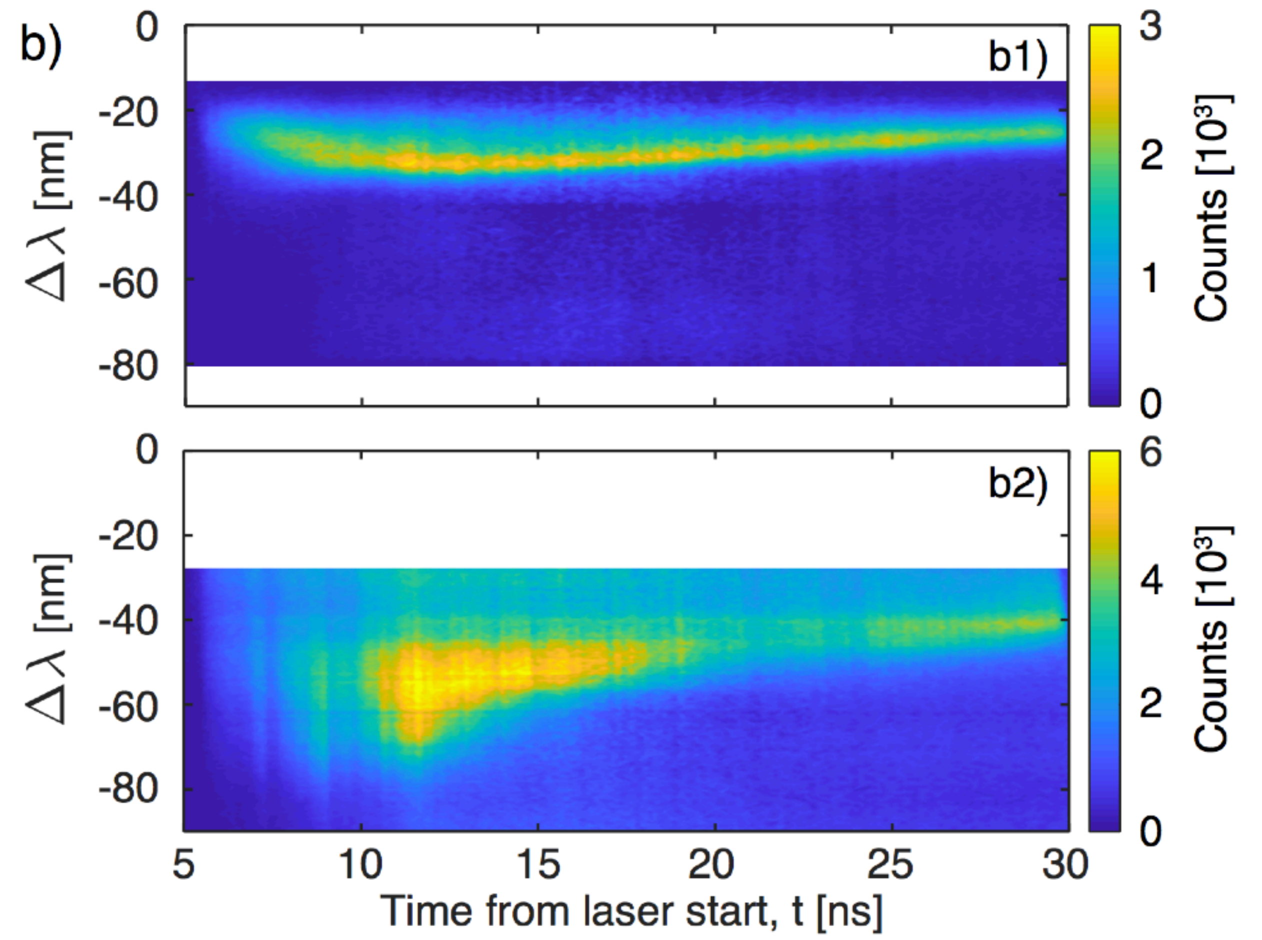
NIF laser system delivers ~ 1MJ in 190 beams



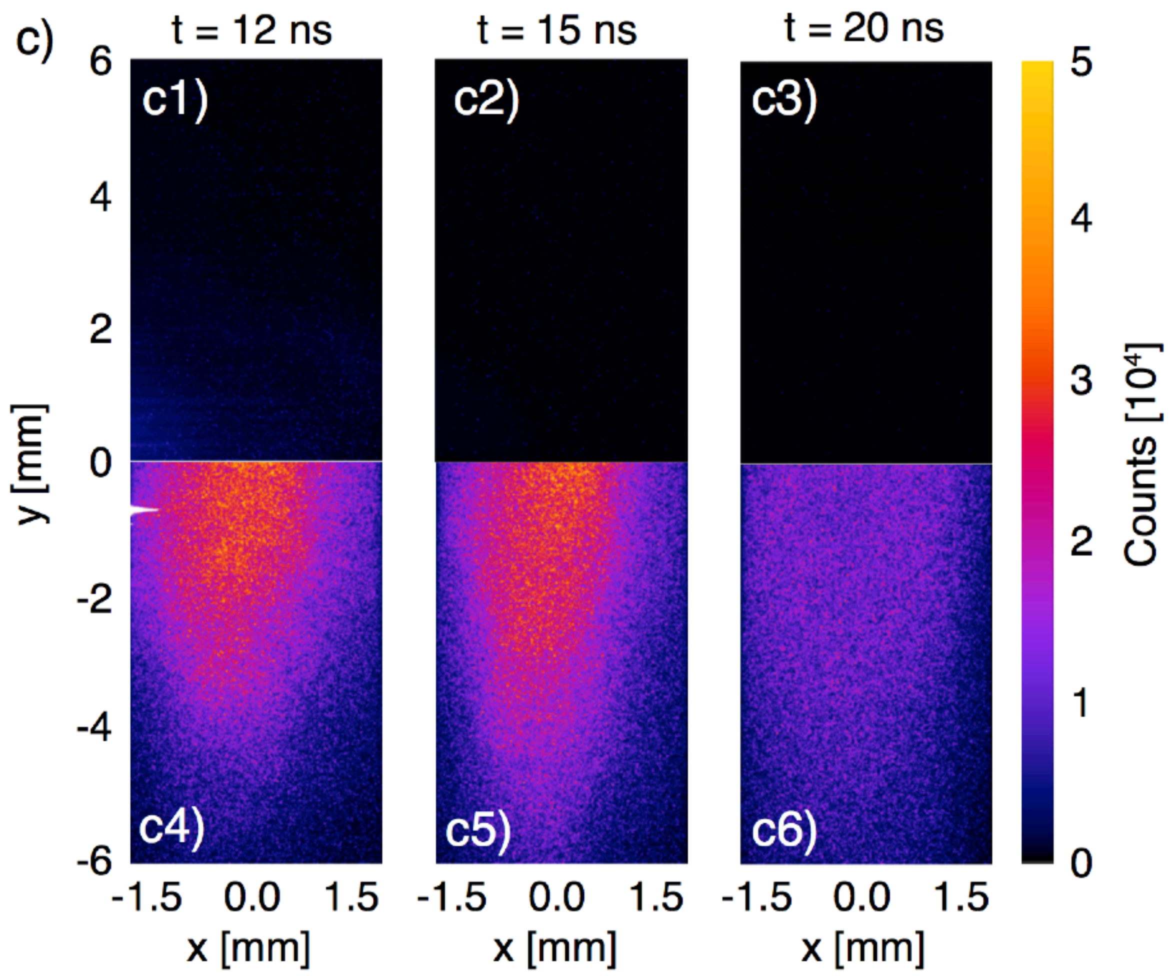
CD2 targets



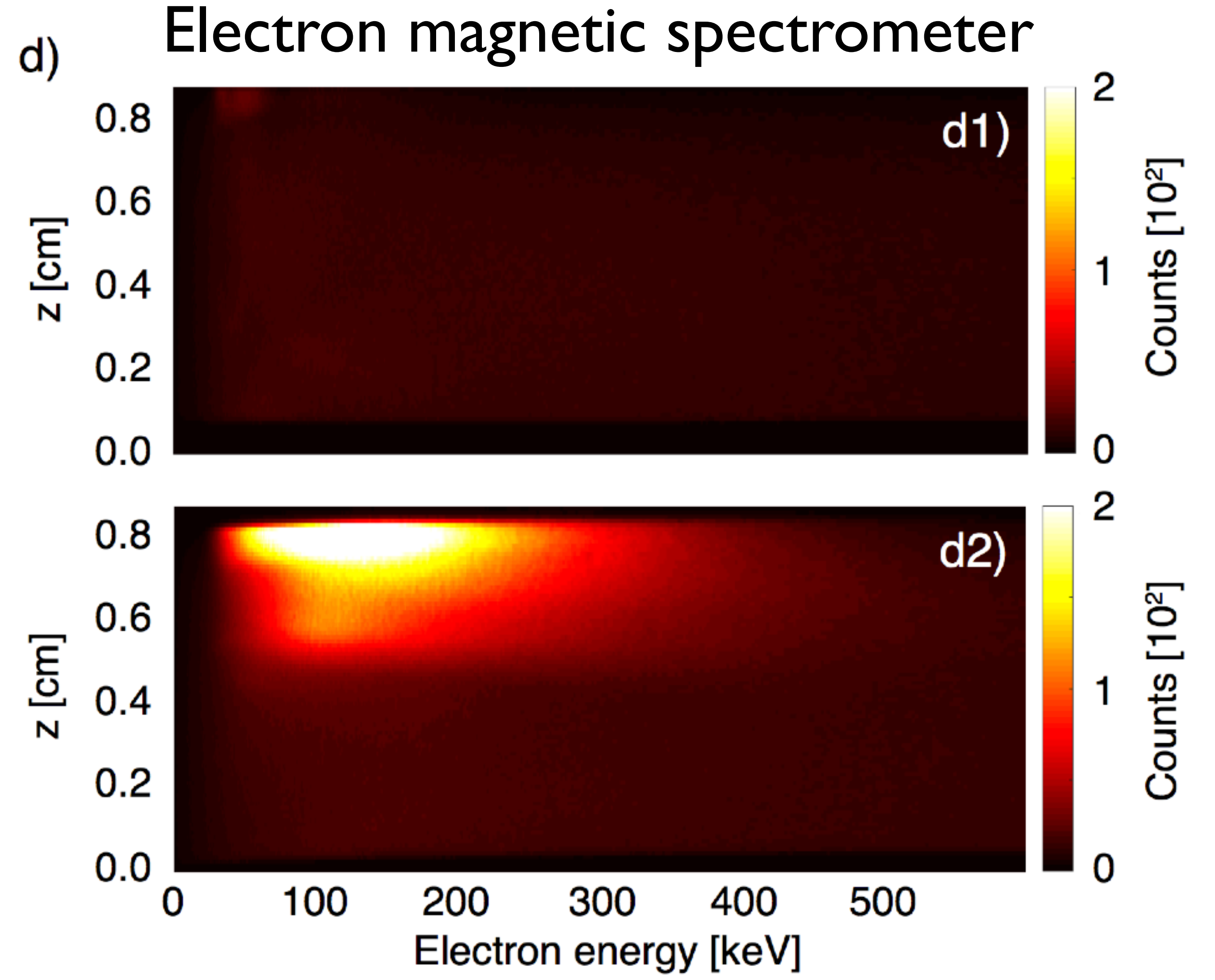
Thomson scattering



Plasma X-ray self emission



Electron magnetic spectrometer



F. Fiuza et al., Nature Physics 16, 916 (2020)

Experimental observation of turbulent collisionless shock

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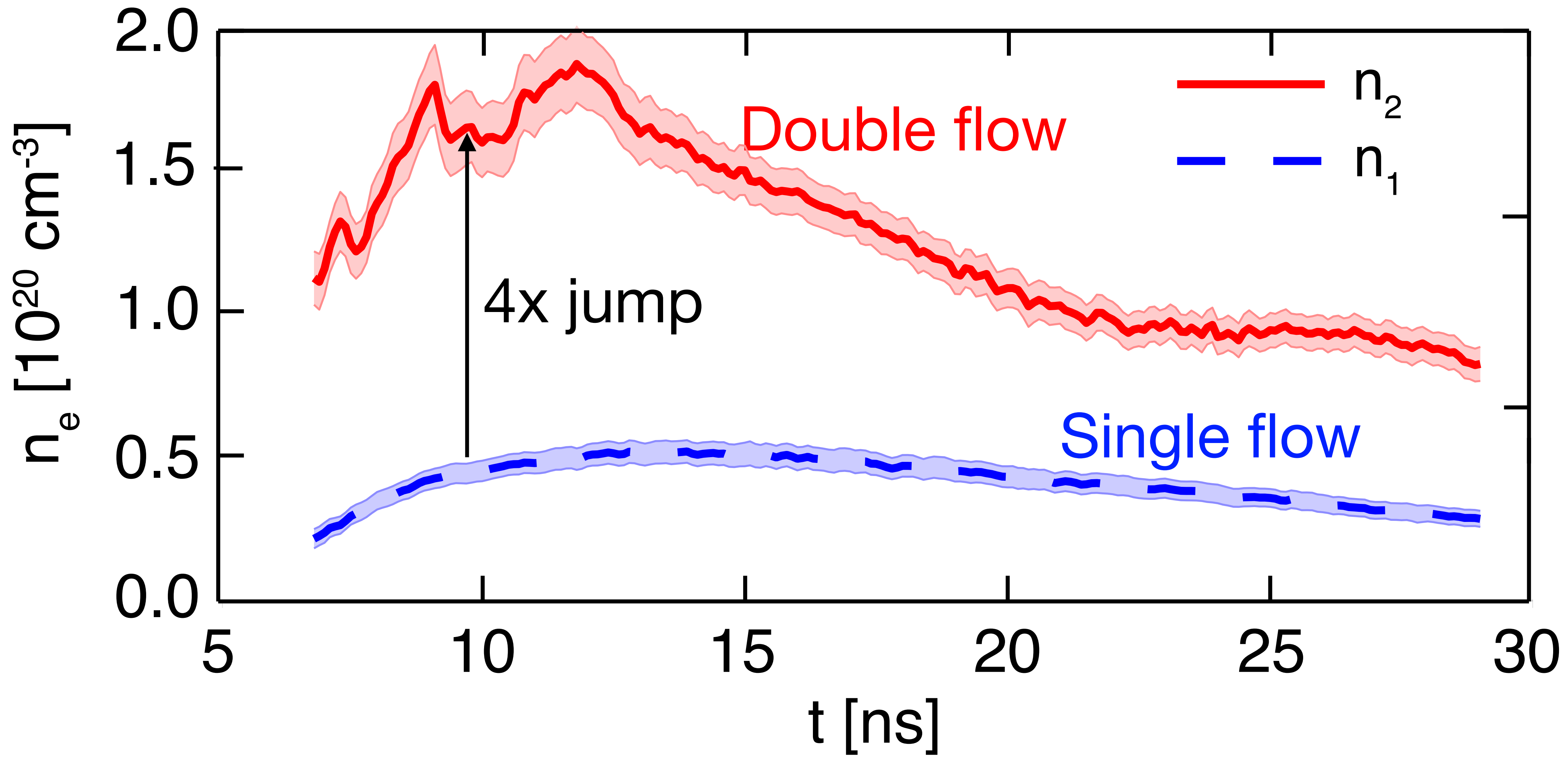
Density evolution of shocked plasma

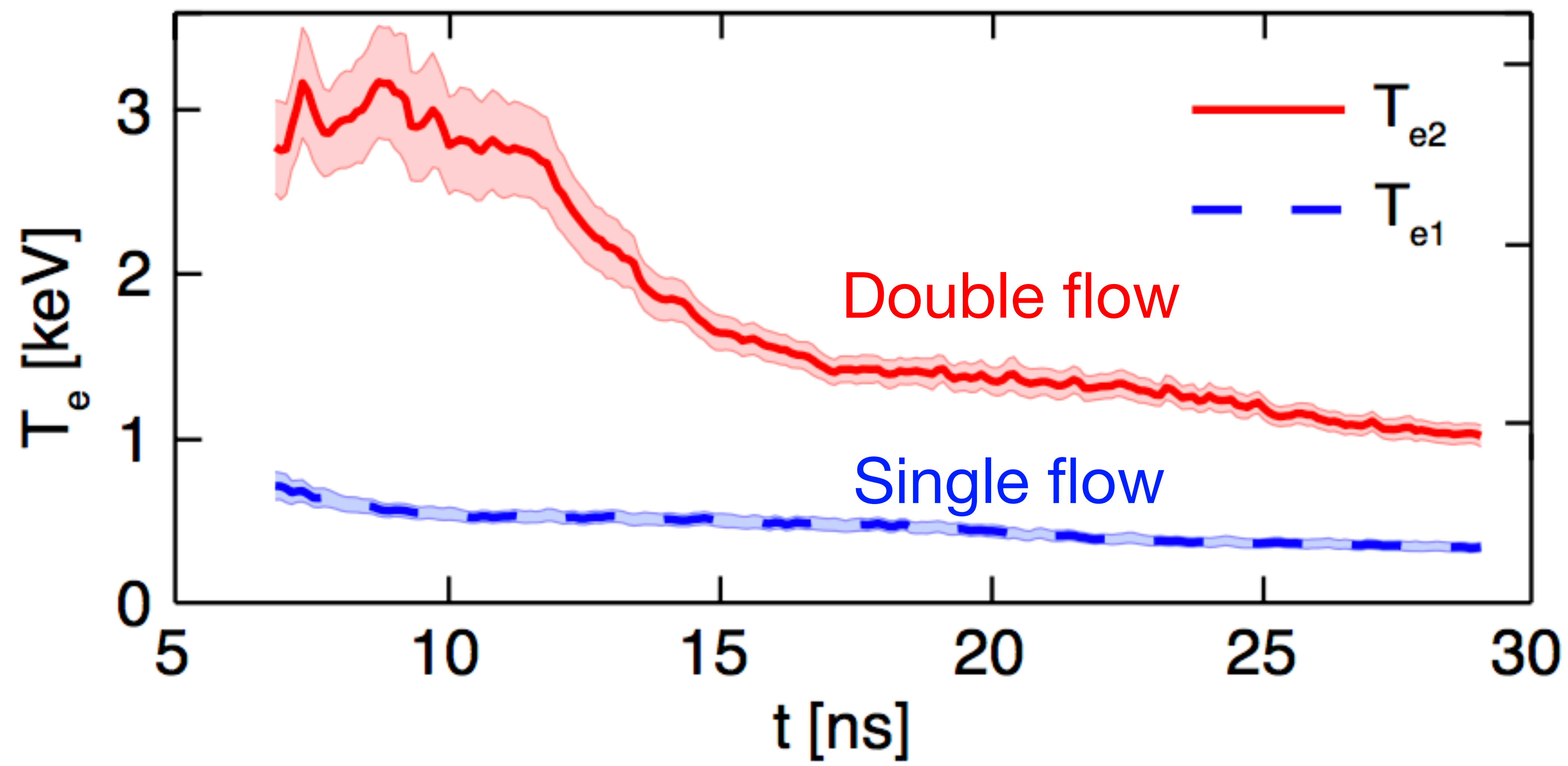


$$v_{\mathrm{flow}} \simeq 1750\mathrm{km/s} \qquad \lambda_{\mathrm{mfp}} \simeq 80\mathrm{cm} \gg L_{\mathrm{system}}$$

$$\frac{n_2}{n_1} = \frac{(\Gamma_{\mathrm{ad}}+1)M^2}{2+(\Gamma_{\mathrm{ad}}-1)M^2} \simeq 4$$

Observed shock is collisionless!

Temperature evolution of shocked plasma



$$\frac{1}{2}m_i v_{\mathrm{flow}}^2 \simeq \frac{3}{2}k_B(T_i + ZT_e) \longrightarrow \frac{T_e}{T_i} \simeq \frac{0.34}{A}$$

Temperature ratio slightly higher than SNR observations (Rakowski 2003, 2006). Electron-ion friction can contribute partially to Te in experiment.

F. Fiuza et al., Nature Physics 16, 916 (2020)

Simulations show consistent Weibel-mediated shock structure

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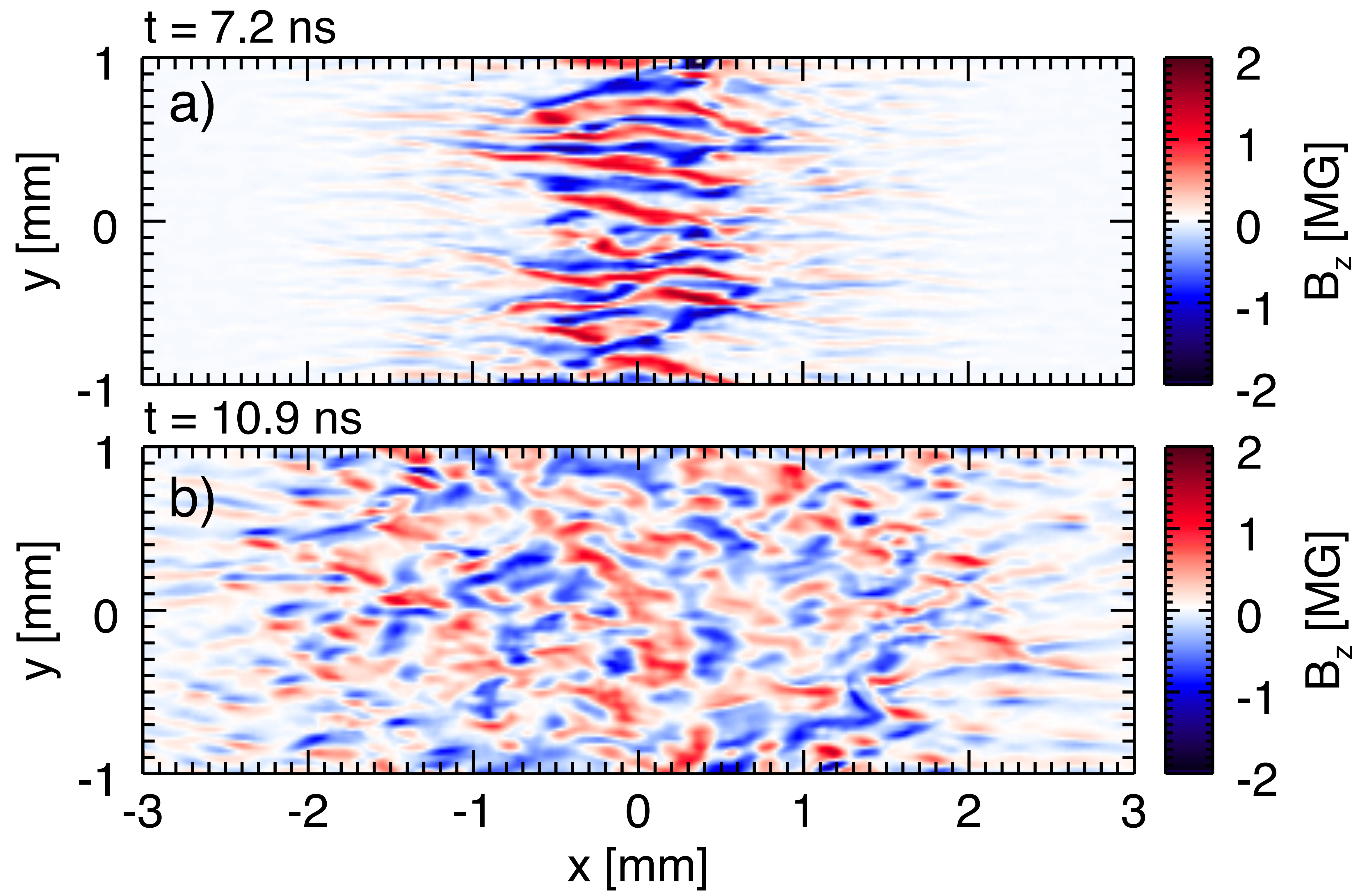
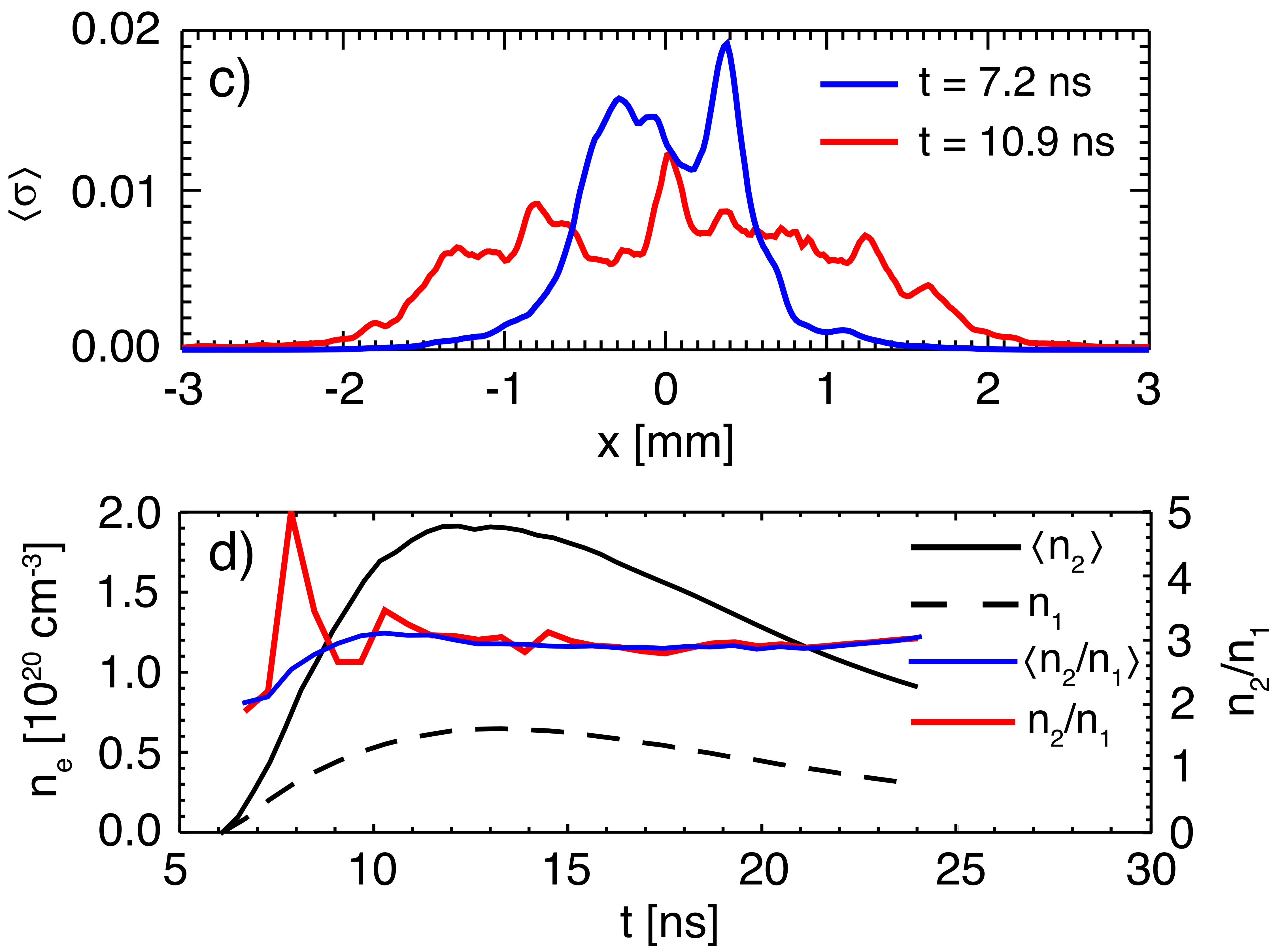
Onset of magnetic turbulence from Weibel instability



Turbulence scale $L_B \sim 200\mu\mathrm{m}$ comparable to ion gyroradius $r_i \sim 300\mu\mathrm{m}$

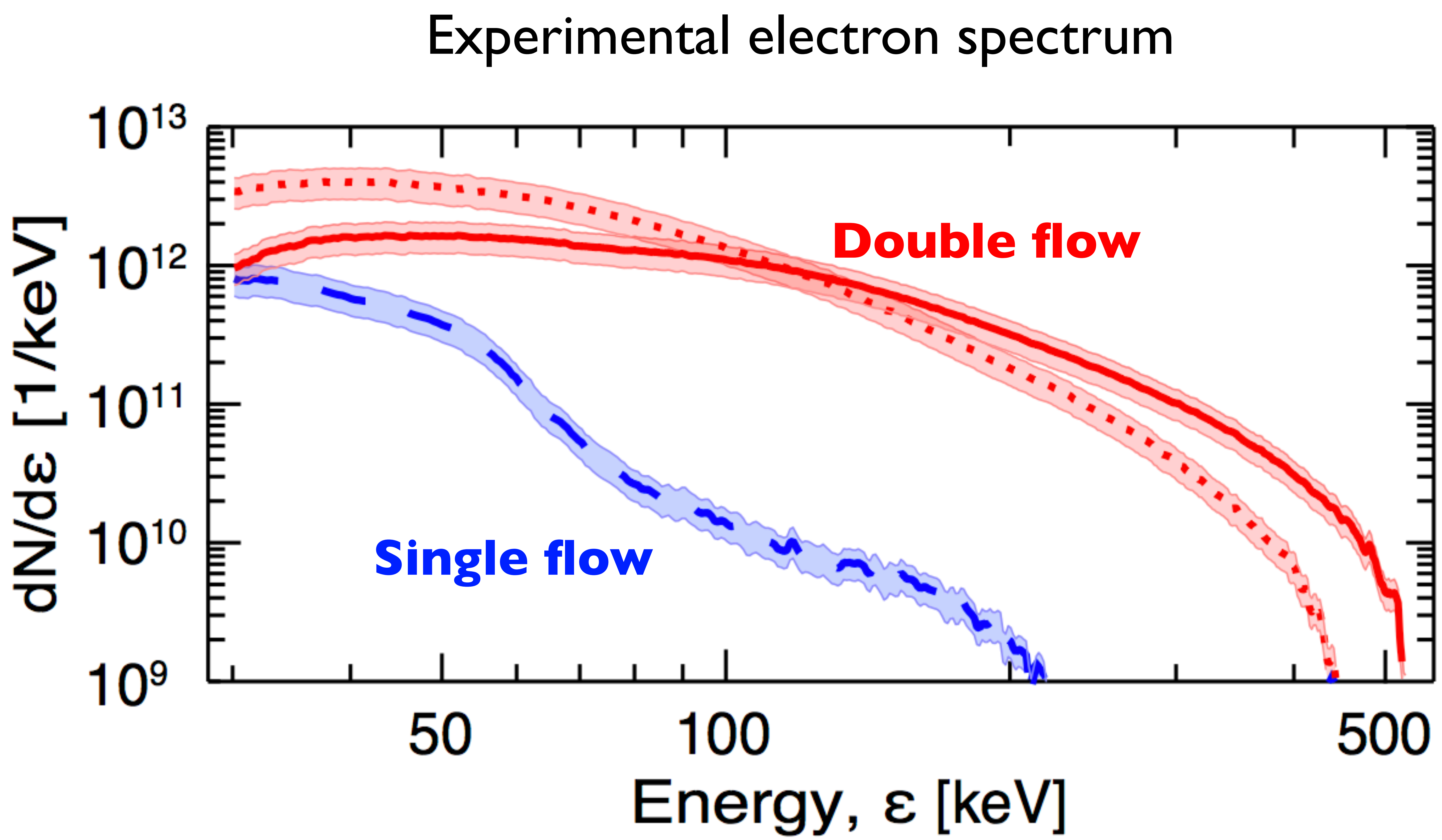
Density evolution consistent with experiments



Shock formation at ~9 ns consistent with experiments

A. Grassi and F. Fiuza, submitted (2020)

Experiments show clear evidence of nonthermal electron acceleration



- Significantly larger (>10x) number and energy of electrons from flow interaction: **electrons must be injected from 3 keV shocked plasma**
- **Electrons are accelerated to > 100x Te in a few ns**
- 500 keV electrons are magnetized at the scale of the shock front: particle escape is primarily transverse
- **Maximum energy given by Hillas limit and consistent with experiment:**

$$\varepsilon_{\max} = |e|(u_{sh}/c)BR_{sh} \sim 500\text{keV}$$

F. Fiuza et al., Nature Physics 16, 916 (2020)

Simulations reveal electron acceleration due to small-scale turbulence in shock front

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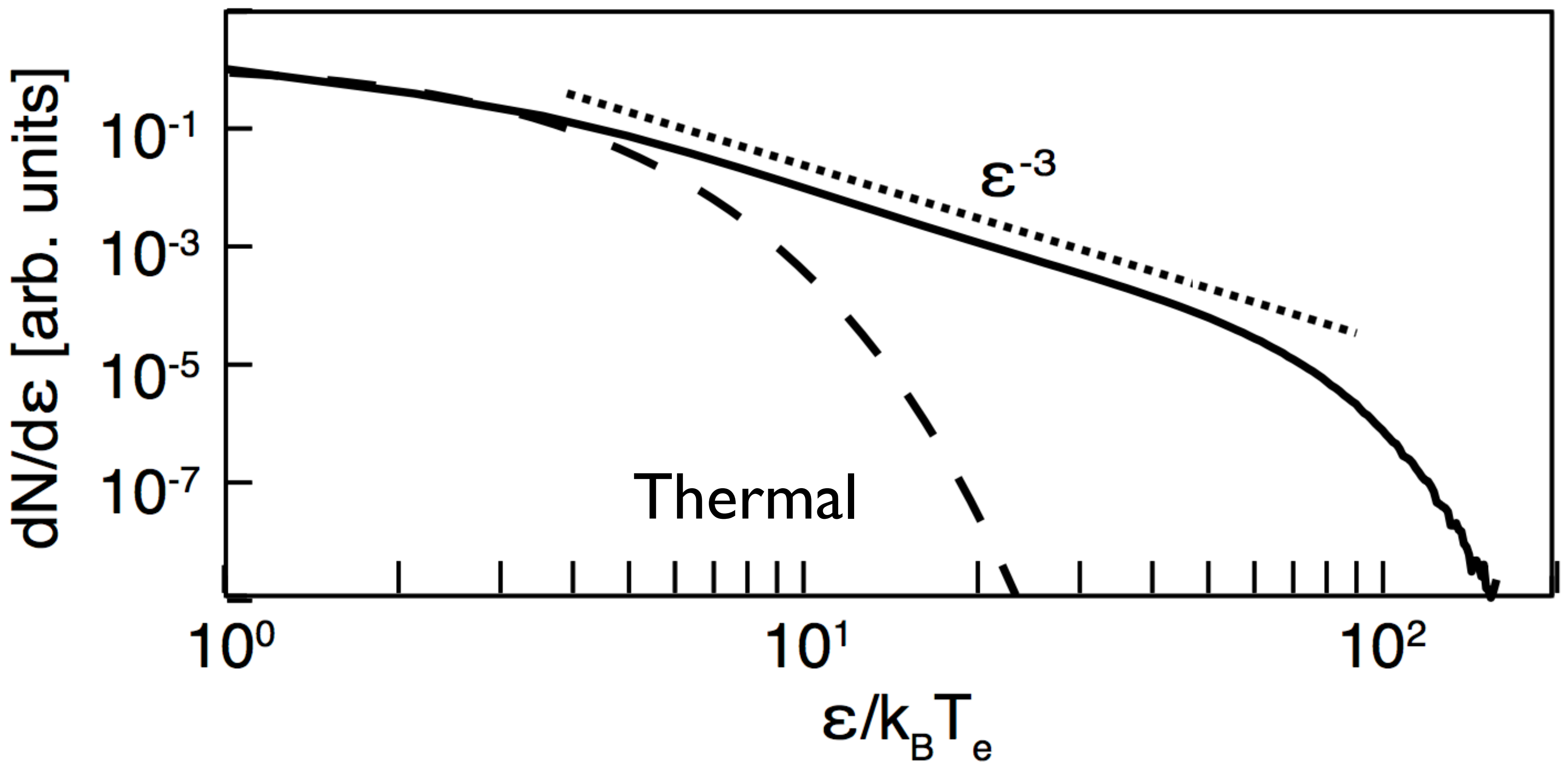
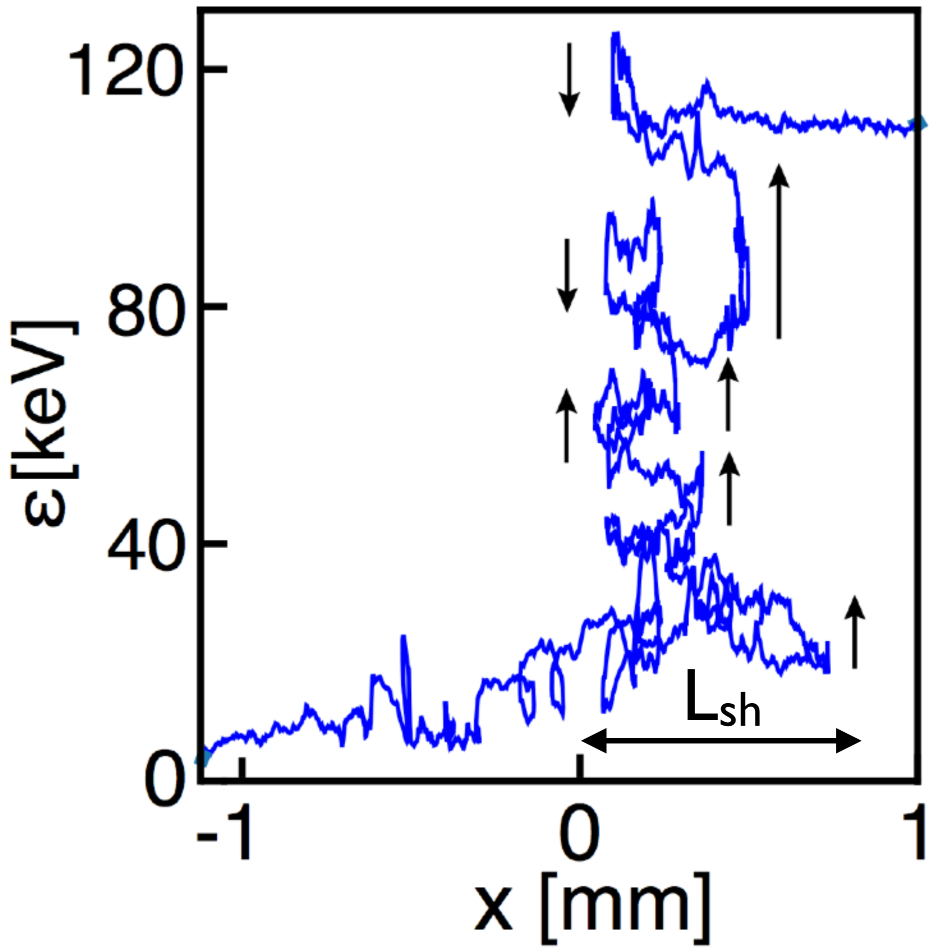
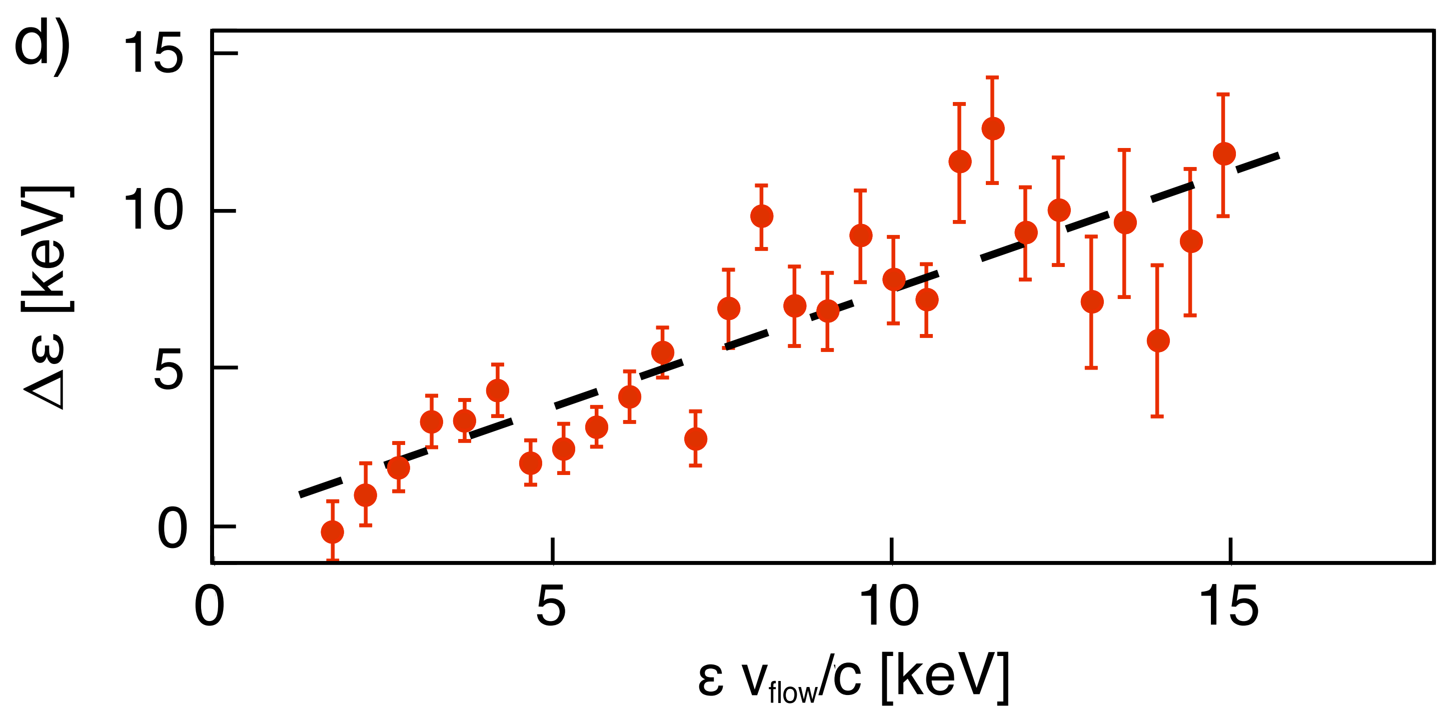
Electron spectrum



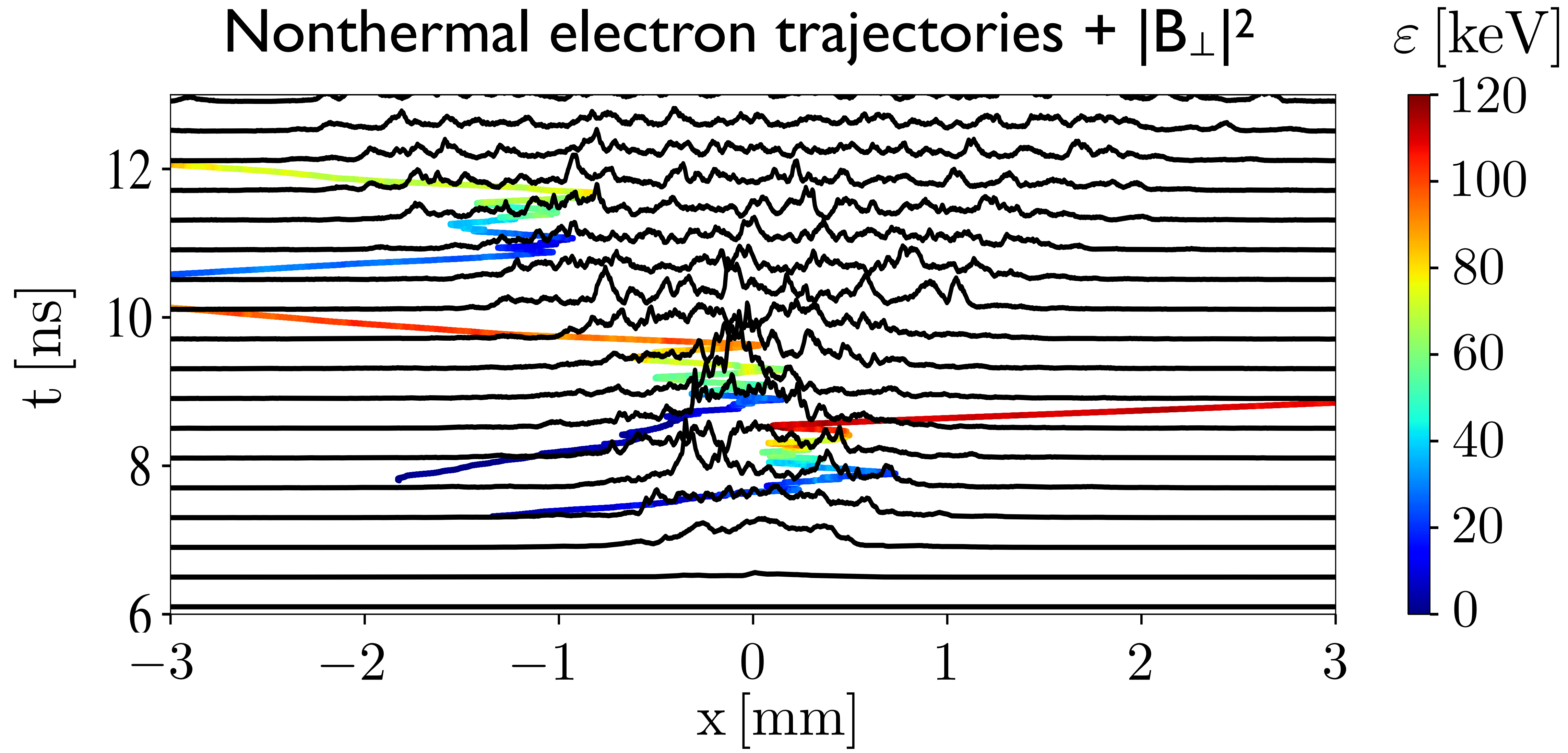
Electron trajectory



I^{st} order Fermi mechanism



Nonthermal electron trajectories + $|B_\perp|^2$



Electrons are accelerated on ns time scale

$$t_{acc} \sim \frac{K(\varepsilon)}{v_{flow}^2} \sim \text{ns} \qquad K(\varepsilon) \sim \frac{2\varepsilon c}{3eB}$$

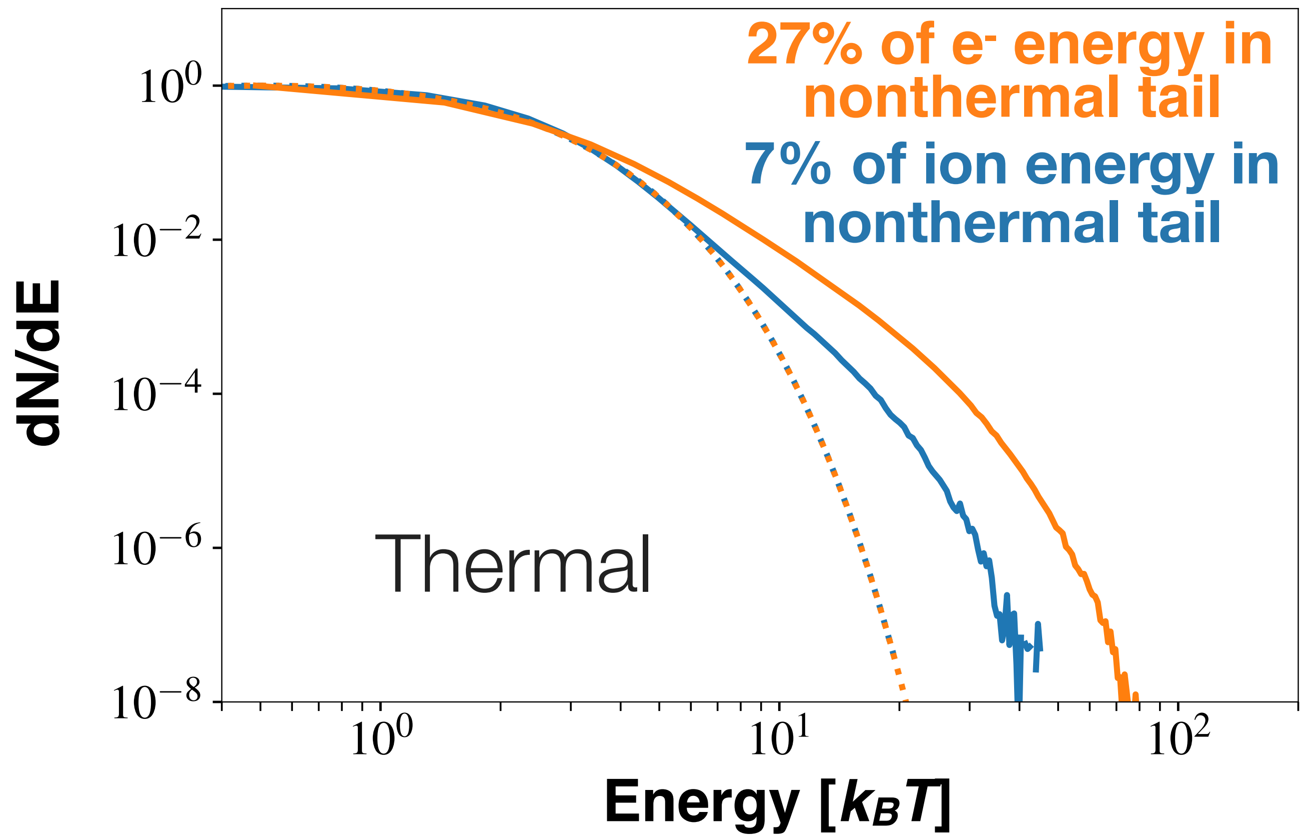
Injected spectral index expected to be steeper than DSA, $p \geq 2$, given than velocity jump experienced is smaller $v_u/v_d \leq 4$

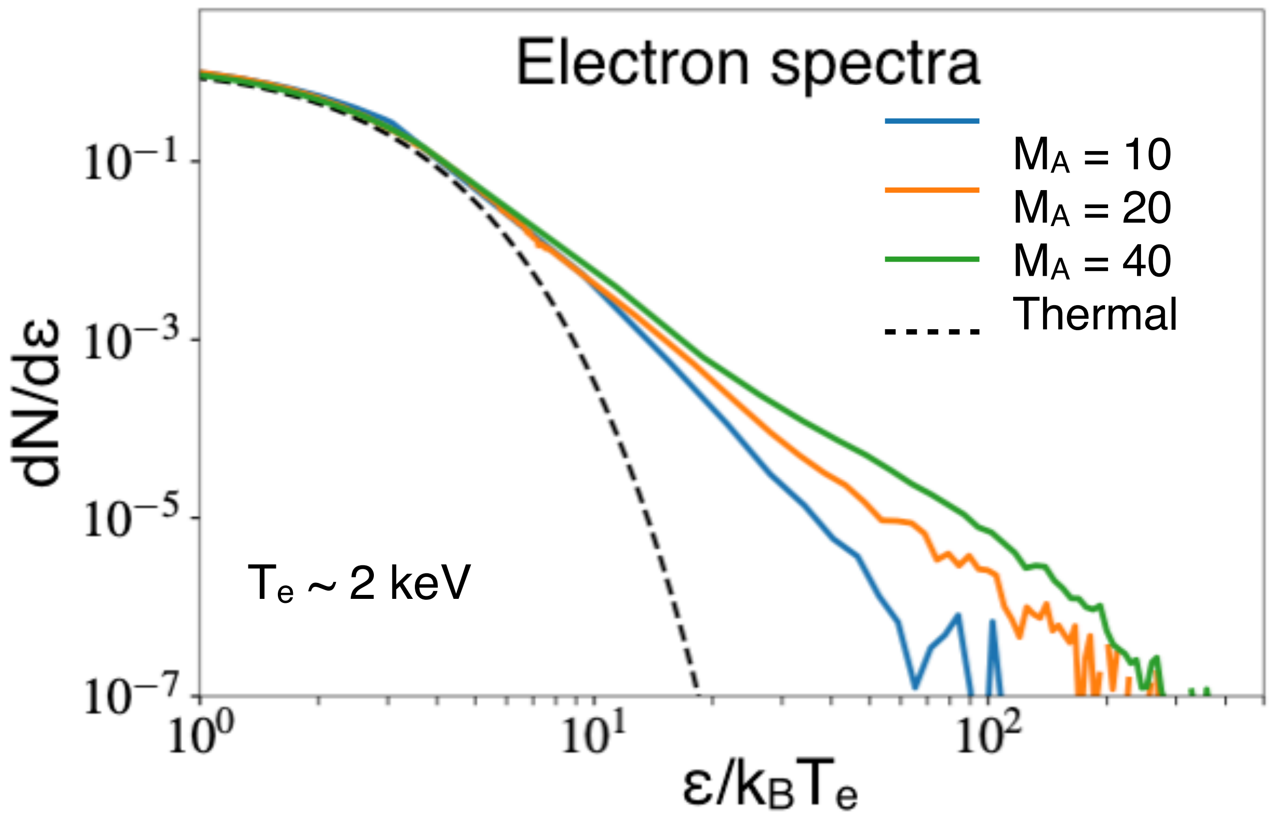
F. Fiuza et al., Nature Physics 16, 916 (2020)

What next?

Extending current measurements and platform

- The fun is just starting! NIF experiments approved for 2021-2023 aim to:
  - **constrain shape of electron spectrum and efficiency from x-ray diagnostics**
  - **measure ion acceleration and relative e-ion efficiency**
  - **probe shock and particle acceleration for variable ambient magnetization**





- Parallel studies are underway in magnetic reconnection, turbulence, and jets (E. G. Blackman & S.V. Lebedev, arXiv:2009.08057)

Perspectives to probe relativistic streaming instabilities

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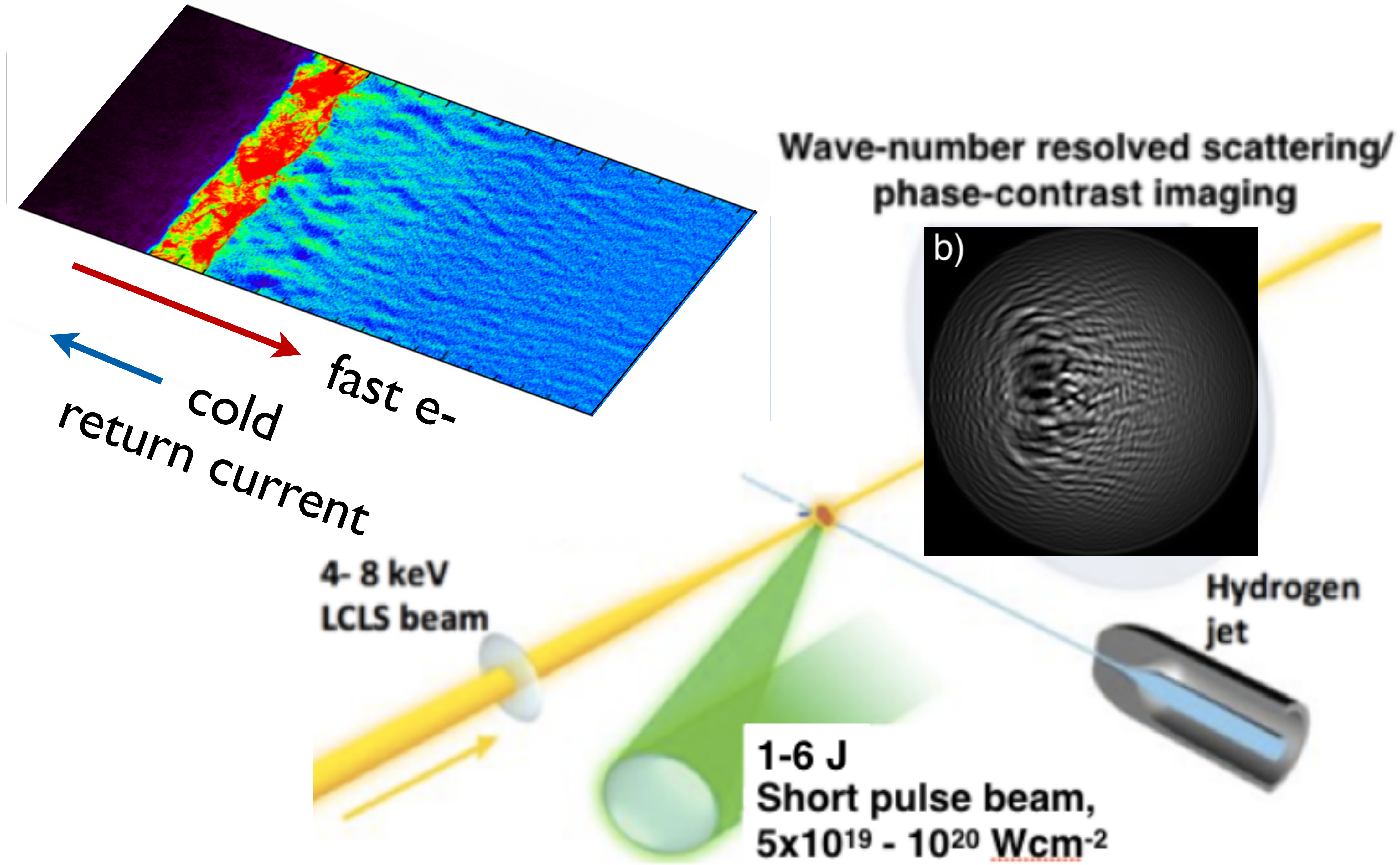
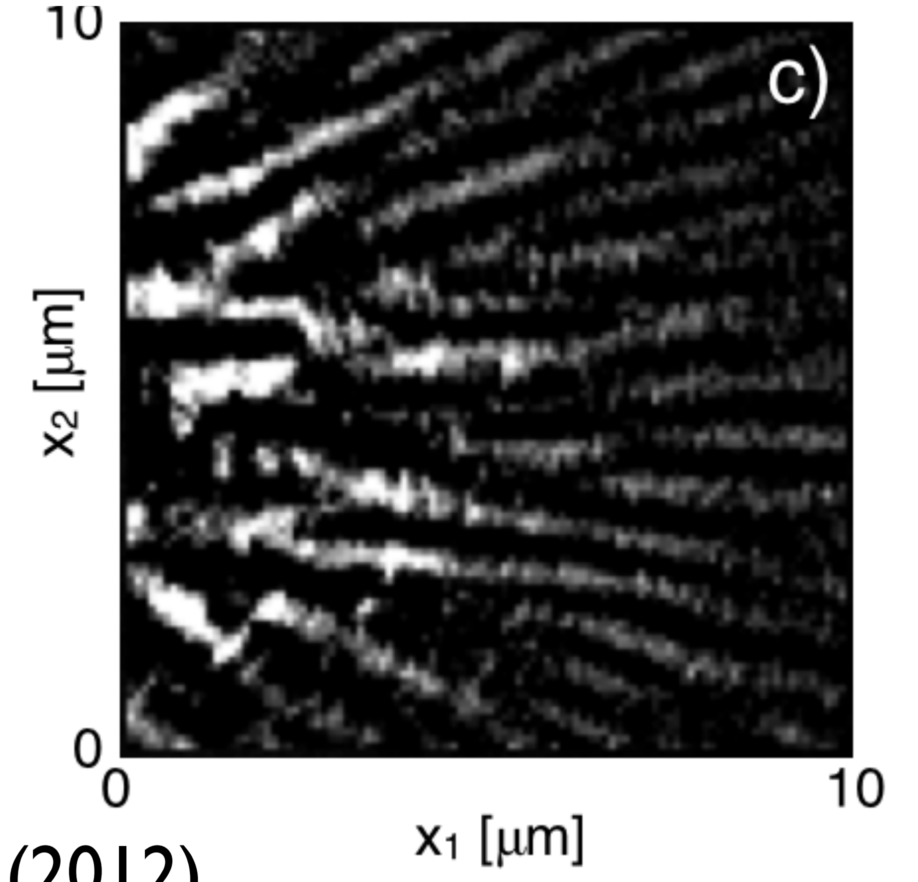


Reconstructed density profile

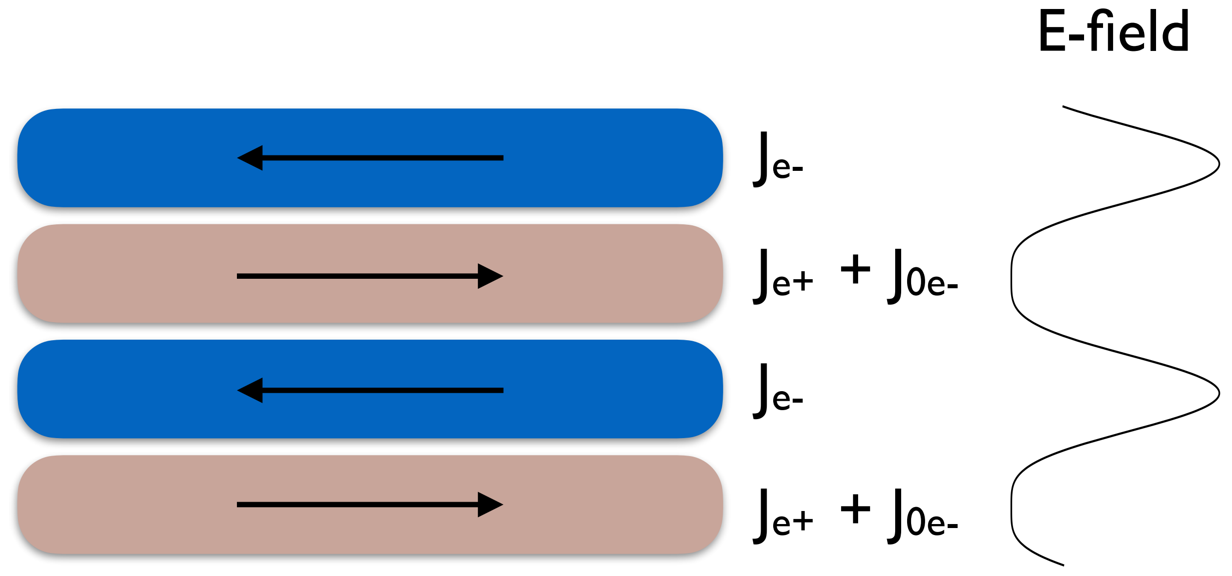


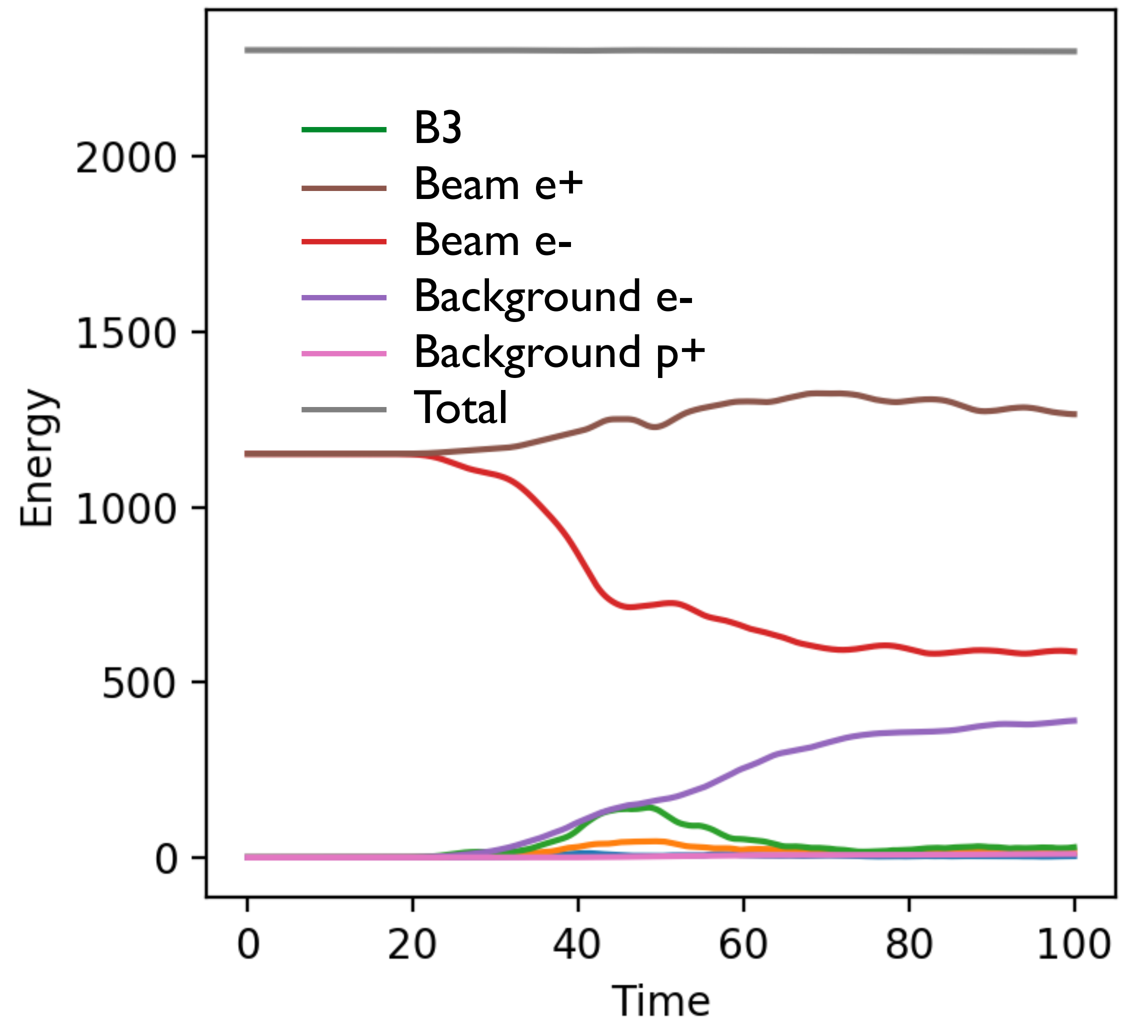
LCLS

F. Fiuza *et al.* Phys. Rev. Lett. 108, 235004 (2012)

10 GeV, 2 nC fireball

e^-; e^-e^+ → e- proton plasma



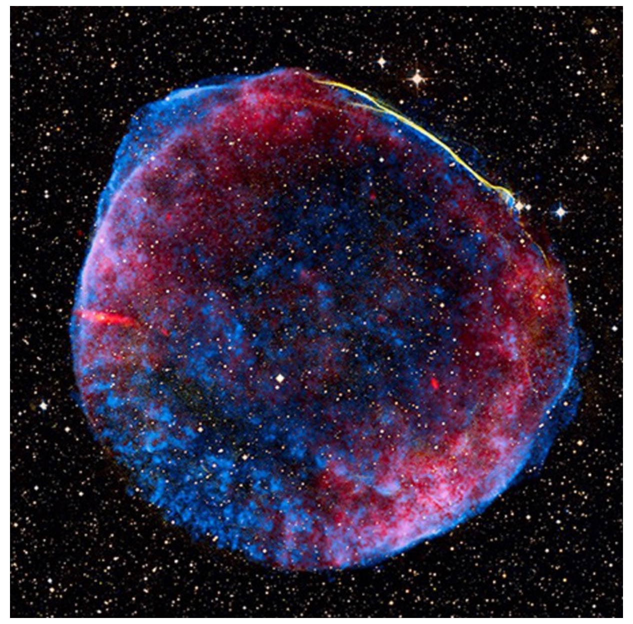


Net inductive E-field associated with magnetic field amplification will preferentially accelerate positrons

P. R. Peterson and F. Fiuza, in preparation

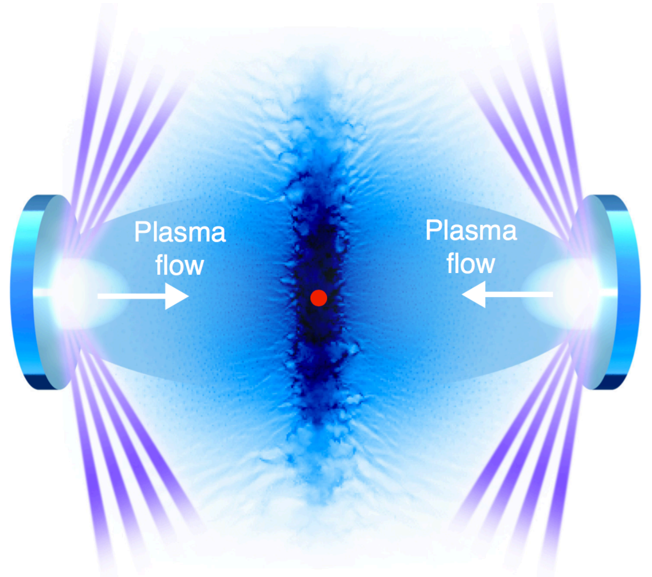
FACET-II
Facility for Advanced Accelerator Experimental Tests

Conclusions



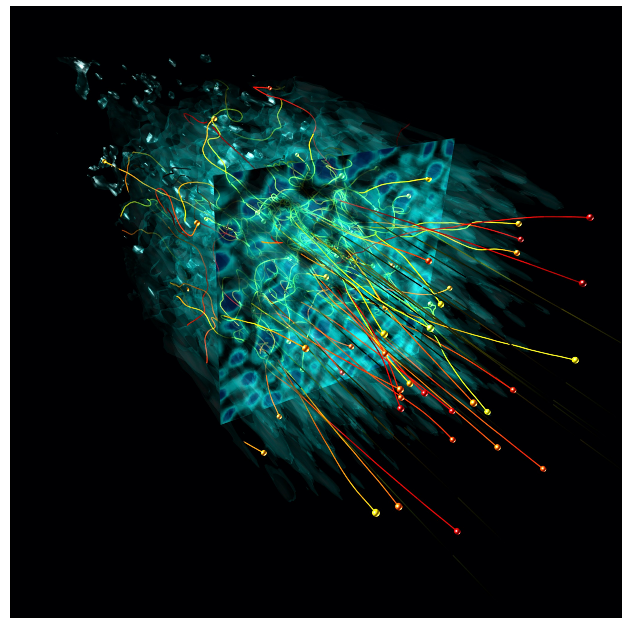
- Shocks waves provide powerful acceleration of charged particles in astrophysics but important questions remain

- Numerical simulations play a critical role in the understanding of the shock physics



- Experiments can be important in benchmarking numerical codes and theoretical models and can complement spacecraft data and astrophysical observations

- Recent experiments probed for the first time turbulent high-Mach number shocks and revealed that this can effectively accelerate thermal electrons to relativistic energies



- Intense lasers and particle beams are enabling studies of magnetic field dynamics and particle acceleration in relativistic regime

We have an open postdoc position to work in this field

SLAC

Stanford University

Postdoctoral Position in Plasma Physics

Work on theory and simulation of particle acceleration in astrophysical and laboratory plasmas

If interested, please email me at
fiuza@slac.stanford.edu